TURBINES

Steam
Water and
Gas

E. T. WESTBURY

Malcolm Gauntlett.

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by
EDGAR T. WESTBURY

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CONTENTS

		PAGE
	Foreword	vii
	Preface	ix
CHAPTER I	Early forms of turbines	1
CHAPTER II	Working principles of water turbines ...	13
CHAPTER III	The evolution of the steam turbine ...	25
CHAPTER IV	Internal combustion turbines	40
CHAPTER V	Hydro-electric generating plants ...	51
CHAPTER VI	Steam power in the twentieth century ...	63
CHAPTER VII	Gas turbines for air, land and marine use	73
CHAPTER VIII	Prospects for future development ...	86
APPENDIX	Glossary	93
	Index	104

FOREWORD

The author of this book has a particular interest in all kinds of turbines, and has been associated with them in various ways. In his early years he lived in the Cotswolds, near a stream which fed three watermills, and was able to watch them working at close quarters. With such tools and materials as were available, he made simple working models of windmills, water-wheels and turbines.

A few years later, in the engine room department of the Royal Navy, he had experience with the management and maintenance of marine steam turbines in battleships, cruisers and small craft. He served in the battle-cruiser *New Zealand* at the battle of Jutland in 1916. In the 1920's he was engaged on the civilian staff of the R.A.F. Apprentice Training establishment at Cranwell, and there made the acquaintance of Frank Whittle, who was soon to become famous as the inventor of the turbo-jet aircraft engine.

When the Royal Navy began experiments in the application of gas turbines to marine propulsion, the author witnessed sea-going tests of some of the first turbine-driven naval gunboats. In these and many other experiences, he has maintained a lifelong interest in all the many and varied types of turbines which now play an increasingly important part in power production.

Apart from writing books and articles on various aspects of engineering practice, he is still as keen as ever on making models, mostly of an experimental nature, including steam and internal combustion engines. He has a firm belief in the value of working models for experimental research and demonstration, also for craft training in engineering, and many of his own models have been put to good use in these capacities.

PREFACE

An engine with only one moving part — what could be simpler ? One may well wonder why it has been found necessary to build complicated engines with pistons, rods, cranks and valve gearing, when it is possible to convert fluid energy to mechanical power by means of a turbine.

Undoubtedly the turbine, so far as its basic principles are concerned, is the simplest of all prime movers, and it was probably the first engine capable of continuous motion that was ever made. Yet it has taken over two thousand years to develop it from a mere toy to a practical and efficient means of producing power, and its apparent simplicity is not only deceptive, but may even be a snare and a delusion. Until less than one hundred years ago, the only really useful forms of turbines were windmills and water-wheels, which utilised free natural forces capable of being easily harnessed, and in which efficiency of energy conversion was relatively unimportant.

The development of modern turbines working by water, steam or internal combustion has been accomplished only by application of the highest engineering skill and science, not to mention untiring effort in tackling innumerable problems in metallurgy and production processes. As in other fields of engineering, progress is usually achieved, not by revolutionary ideas and inventions, but by a process of evolution in which many men, few of whom would claim to be brilliant, have contributed some small but significant part. One of the greatest inventors of the 19th century, Thomas Alva Edison, said that successful invention was " five per cent. inspiration and ninety-five per cent. perspiration."

Even at the present day, the turbine is not the complete answer to all mechanical power problems. There are still many purposes for which the reciprocating or " piston " engine is better suited, and often more efficient in terms of power in relation to fuel consumption. Much remains yet to be done in improving the efficiency of turbines and making them easier to produce ; this

applies particularly to the internal combustion turbine, but holds good in all cases, especially in the smaller sizes of power units. It will be a long time before turbines supersede all other forms of engines—if they ever do—but there is no doubt that they are marching steadily on.

In this book, an attempt is made to present the story of the turbine, in all its forms, as simply and lucidly as possible, but with due regard to accuracy in all essential details. It is often thought that books on engineering and scientific subjects, in order to be technically informative, must necessarily be dry and tedious, but this is a fallacy, and has often handicapped teaching of these subjects, or rendered them unpopular among non-specialist readers.

There is, indeed, a world of adventure to be found in engineering, and it is hoped that readers will find much to interest them in the history of turbine development, and the people who have been concerned with it, just as much as in the descriptions of the actual turbines. The examples selected and illustrated are intended to show principles rather than constructional details, and while reference has been made to the physical laws which govern the design and operation of turbines, it has not been considered necessary to burden the reader with formulas and mathematical data. These are undoubtedly necessary to more advanced study of the subject, particularly for readers who may be seriously considering taking up a career in turbine engineering, but they are not essential to an intelligent understanding of general principles. There are many people who regard theory and practice as diametrically opposed to each other, but in actual fact they are complementary, and each is useless without the other; but depend on the application of sound logic and common sense.

No apologies should be necessary for recommending the application of one or two simple experiments to demonstrate the principles of turbines, such as impulse and reaction forces. No more convincing method of driving home knowledge of physical laws can be found than putting them to these simple tests. One may go still further, and make working models in which factors which influence efficiency may be investigated. Although it would be difficult to make really elaborate models of modern steam and internal combustion turbines, the simpler types of windmills,

water turbines, and even steam impulse turbines, can be constructed without the need for special tools and equipment. Much can be learned from these simple models, and they whet the appetite for further experimental investigation which may have far-reaching results. The well-known tale of James Watt and the tea-kettle may be fact or legend, but it is certainly true that many a distinguished career in engineering has started from experiments with a simple model.

Due acknowledgments are made to the manufacturers of all kinds of turbines, who have kindly furnished information and illustrations of their products. The assistance of Miss Elizabeth Mallinson in the preparation of art work is also duly appreciated.

CHAPTER I

EARLY FORMS OF TURBINES

EVER since the dawn of history, men have sought to harness the forces of nature to assist them in their domestic tasks and industries. At first, only those forces which were already available in a mobile form, such as wind or running water, could be usefully employed, but at a later date it was found possible to utilise heat energy produced by the combustion of fuel, and this led to the development of the steam engine. At the present day heat engines in various forms produce most of the mechanical power for industrial and transport requirements, but natural forces, particularly water power, are still extensively employed.

One of the most important engines, or prime movers, as they are generally termed, for the production of power on a large scale, is the turbine, which is made in various forms to make use of either steam, water or air pressure. Although turbines are generally regarded as the most modern development in engine design, they are very old in original conception, and attempts were made in very early times to put them to practical use.

Before discussing the history and development of turbines, it is advisable to have a clear definition of what the term turbine really means. Most people have a vague idea that the working parts of a turbine have a rotary motion, but there are many kinds of engines in which this applies, and not all of them are turbines in the true sense of the term.

All mechanical prime movers work by the application of fluid pressure, in the forms above mentioned, and although they vary widely in design, there is a general similarity in the

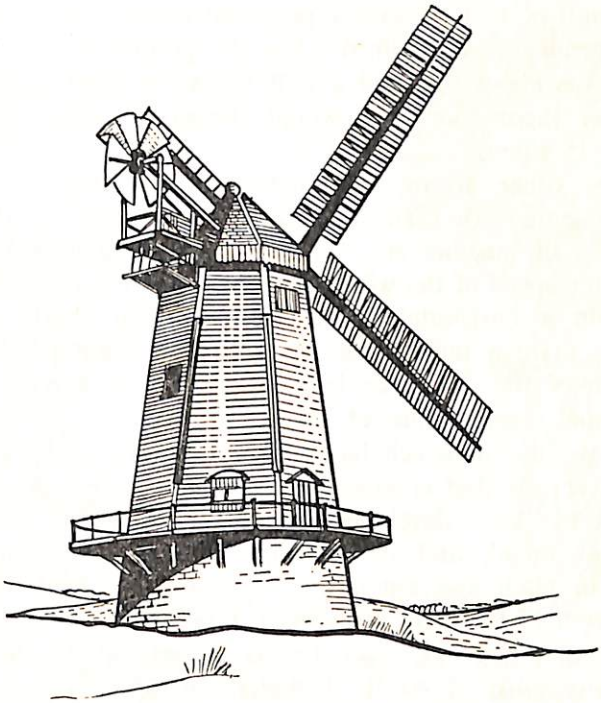
principles employed. In the most common type of reciprocating engine, the pressure acts on a piston, which in turn transmits motion through a connecting rod and a crank, to a rotating shaft. An engine of this type can be made to work more or less efficiently at any speed, because the pressure is not allowed to escape before it has performed some work by moving the piston, or in other words, by *displacement*. Some kinds of engines have been devised in which the connecting rod and crankshaft are dispensed with, though some form of piston, such as a closely-fitting vane or toothed wheel, having a rotary motion, is still employed. Such engines are properly known as rotary displacement engines, and though they are often confused with turbines, they are in a distinct class of their own.

In a true turbine, there is no close-fitting piston ; the working pressure is converted into *kinetic* energy, or in other words, energy of motion, by passing it through nozzles or other suitable passages which exchange its pressure for velocity, and this in turn is utilised to act on blades attached to a rotating shaft. The simplest example of a turbine is an ordinary windmill, in which air moving at a relatively low velocity—often only a few miles per hour—acts on inclined vanes or blades in such a way as to cause rotation of the shaft on which they are mounted.

The origin of the windmill is lost in antiquity, and it would be idle to conjecture where or by whom it was first invented. Primitive man undoubtedly became impressed by the way the wind deflected trees and plants, or moved objects bodily, especially those floating on water. When the first rude boats were fashioned from logs or bark, it was soon found that their movement could be assisted by wind, and the use of a sail of some kind was a logical development. It is probable that this was the earliest form of "wind motor"; later, when a need for rotary motion arose, the idea of fixing a number of masts and sails radially around a shaft must have occurred to many people.

The old windmills which were once a familiar landmark in many European countries, but are now rapidly becoming extinct, were usually made with four sails or "sweeps," though six were occasionally used. Sometimes they were mounted on

poles, with central pivots so that the whole mill was capable of rotation; in other cases the mill was stationary and only the head made movable. In either case the shaft axis, which was usually inclined slightly to the horizontal to keep the bearing thrust always in one direction, could be brought to face the direction of the wind, by means of a windlass operated either by hand, or automatically by a small tail mill. Power was usually transmitted by means of wooden gear wheels to a



An old English four-sweep windmill, showing tail mill for turning the head into the wind.

vertical shaft running down the centre of the mill, from which the millstones and other machines on the various floors were driven. In Holland, and also the fen country of Britain, windmills were mainly used for pumping, a most essential service to prevent the low-lying land from becoming inundated.

Although the sails of these old mills were often built up from slats or narrow boards instead of canvas, the analogy of

the sailing ship is still applicable, and they were capable in many cases of reefing or shortening sail in order to cope with varying wind forces. Sometimes this was done by altering the angle of the entire sail frame, like the blade of a variable-pitch propeller, and in other cases by tilting the whole set of slats so that air was spilled between them. The latter method required less effort, but involved more complicated linkage of the slats, so that the adjustment did not interfere with the free rotation of the windshaft. In a 10-mile per hour breeze, a 4-sweep mill of 15 ft. diameter produced about 1 h.p., and most efficient results were obtained when the peripheral speed at the sail tips was about two and a half times the wind speed. The mill under these conditions would therefore rotate at slightly less than 45 r.p.m.

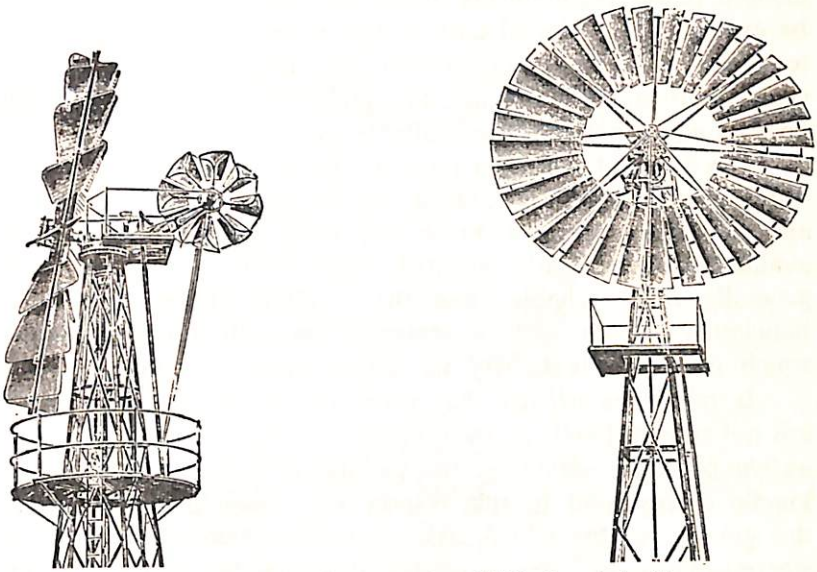
Many other forms of windmills have been produced, including some with vertical shafts. An example of this type is found in the anemometer, which is used by meteorologists to measure the speed of the wind. This has four hemispherical cups rotating in a horizontal plane, on a vertical shaft which is geared to drive a tachometer or revolution counter. It works by reason of the difference between the forces exerted on the concave and convex sides of the cups.

A type of mill which has been extensively used during the last 100 years is that commonly termed the American windmill, though it has been developed in several countries. It is built entirely of metal, and has multiple blades, which are often variable in pitch and automatically governed. Such mills are usually from 15 to 20 ft. in diameter, producing from 1 to 3 h.p., and are mounted on steel towers about 30 ft. high, but occasionally mills of 40 ft. diameter, on 40 ft. towers, which develop 6 to 12 h.p. have been commercially manufactured, and still larger ones specially built.

Despite the greater number and aggregate area of the blades, the efficiency of these mills is not so much greater than that of the old 4-sweep mills as might be expected. They are sometimes steered into the wind by a large fantail, though the larger ones have a tail mill with reduction gear, driving on a large gear ring on the pivot head, for this purpose. When used for pumping, the windshaft is either direct-coupled or geared to

a crank, which drives a long connecting rod leading to a pump at the base of the tower.

The speed and torque produced by a windmill is influenced by the angle at which the sails, sweeps or blades are presented to the wind. If they are set at a fine angle of incidence (i.e., nearly at right angles to the shaft axis) the speed in relation to the wind will be high, and the torque low. By increasing the angle of incidence, the speed can be reduced and the torque increased. It is thus possible, by adjusting the angle, to keep a



Two examples of all-metal multi-blade windmills.

windmill running at a fairly constant speed, but it is important to remember that the actual *power* developed depends on torque multiplied by speed, and must necessarily vary according to the speed and force of the wind.

Although most windmills are, for reasons of convenience, designed to run at low speeds, there are occasions when higher speed is necessary, as for driving electrical generators. This can be done by the use of gearing or belt drives, but in recent years a new type windmill which runs at much higher speed has been developed. This usually has two blades of very fine pitch, and in order that it shall not be slowed down by its own

resistance, the shape and cross-section of the blades are aerodynamically designed ; it is in fact, an inversion of a fine-pitched aircraft propeller. Mills of this type are generally fairly small, and are used for charging batteries for radio and lighting in remote districts. The rotating cowl fitted to chimneys to assist draught is a form of windmill or air turbine.

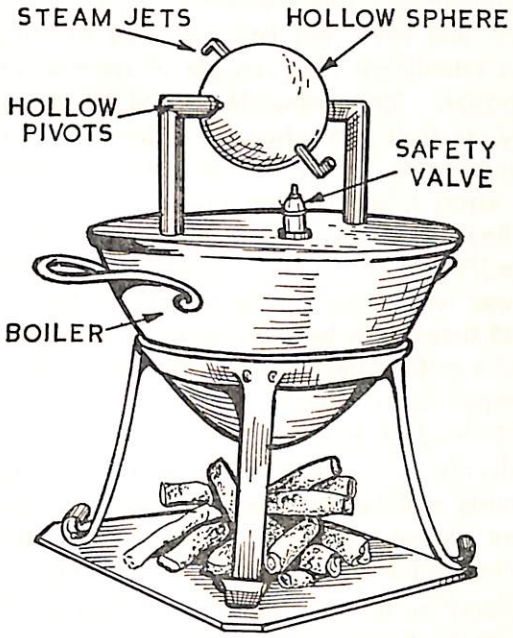
Windmills provide free power, but are strictly limited in this respect, and there are serious structural problems in making them much more powerful ; they are certainly inadequate for modern power requirements unless new principles of design can be evolved. Their initial cost is high nowadays, and in addition to their restrictions in respect of location, and possible unreliability in calm weather, this puts them in an unfavourable position compared to other available forms of power.

The origin of the water turbine may be found in the primitive water-wheel, which is almost as ancient as the windmill, and has been used for much the same duties. Though its availability is similarly affected by climatic conditions, it is generally more reliable than the windmill if its location is judiciously chosen, near a waterfall or swift running stream, which is not likely to dry up under normal conditions.

It might be argued that some old types of water-wheels are not true turbines, as their power is derived largely from the *weight* of water acting on the paddles or buckets, rather than kinetic energy, and in this respect they resemble more nearly the gravity motors which have sometimes been used as toys, where sand or lead shot is used to drive paddles or pulleys. But the later types of water power motors are true turbines, in which efficiency depends on the kinetic energy of a stream or jet of water moving at high speed. These turbines are of two types, differing in their design to suit relatively low and high falls respectively.

Generally speaking, the problems involved in the design of both windmills and water turbines are less complex than they are in steam turbines, and the practical development of these only became possible in comparatively recent years. Nevertheless, an account of a steam turbine was recorded as early as 150 B.C. by Hero of Alexandria, though it is not quite clear whether he was actually the inventor. It was not called a turbine, but it demon-

strates working principles which are still employed in steam turbines up to the present day. There are various descriptions and drawings of this device, and also dispute as to the pronunciation and spelling of its name; but according to the most reliable reference literature available, it was called the Aeolipile (from the Latin *Aeolus*, the god of the winds, and *pila*, a ball). Many models have been made from Hero's description, and most of



A model of Hero's Aeolipile, the earliest known form of steam turbine.

them comprise a low-pressure steam boiler, on which is mounted two columns which form both steam inlet pipes and bearings for a hollow sphere mounted between them, so as to rotate freely. Two or more hollow arms project radially from the sphere, and are bent at a tangent to the path of rotation.

When steam is admitted to the sphere, it issues from the ends of the arms at high velocity, and produces a reaction which causes the sphere to rotate in the other direction at high speed. This may be said to be the very earliest form of engine capable of

continuous motion, though Hero also describes a primitive form of engine in which steam or hot air was used to displace water from one vessel to another, and thereby cause a change of balance, which, acting through ropes and pulleys, was used to control the opening and closing of temple doors. Incidentally, this principle was utilised centuries afterwards by the Marquis of Worcester, and still later by Savery in his steam pump, but neither of these devices could be directly applied to turning a shaft continuously.

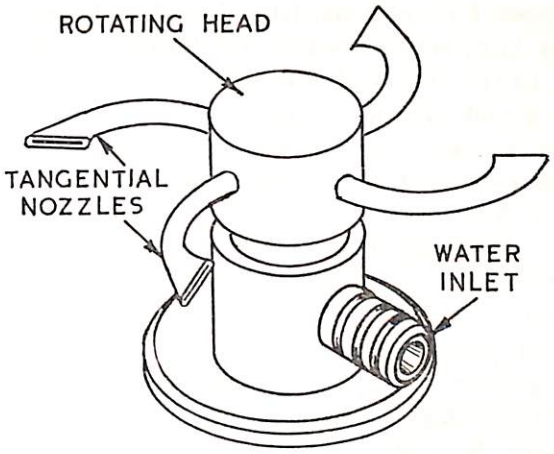
The Aeolipile was very inefficient and wasteful in its use of steam energy, and could not be considered as much more than a toy, but it established the principle of reaction as a means of producing power. This principle should be examined a little more closely, as it is very often misunderstood, despite the fact that it is increasingly employed nowadays, not only in turbines, but also in aircraft, rockets and missiles. Many people fail to understand how these can be propelled in outer space, where, as they say, the jet has "nothing to push against." When a rocket-driven car was tested some years ago, its rather slow start was criticised, and suggestions were made that it would get away much quicker if it was first backed up against a wall; but this is a fallacy, as experiments will show.

If one is holding a garden hose with a plain nozzle, and someone suddenly turns on the water at full pressure, a distinct push backwards will be felt, due to reaction. The same effect causes a lawn sprinkler to rotate in the opposite direction to the spray of water which emerges from it. In fact, this common modern appliance is nothing more than a form of Hero's turbine working on water pressure instead of steam.

To understand the principle of reaction more fully, imagine a boiler or other vessel containing pressure, freely suspended so that it is capable of moving in any direction. So long as the pressure acts equally on all the interior surfaces, and no leakage takes place, a condition of equilibrium exists, and there is no tendency to motion. But if a hole is made in one end of the boiler, causing a rapid escape of pressure, and consequently destroying the balance of pressures on the inside of the vessel, it will move at a high velocity in a direction opposite to the escaping stream.

This effect accounts for the disastrous results which occur

when a boiler bursts or springs a serious leak; also for the recoil of a gun when the shot is fired. But it is very brief and transitory in such cases, and can only be maintained continuously if means are available for supplying pressure fast enough to make up for that which is lost. In a rocket, this is obtained by means of a solid or liquid propellant fuel charge, capable of burning very rapidly and discharging enormous volumes of expanded gas. A steam turbine, on the other hand, must have its jet or jets designed to suit the rate at which it can be supplied with steam at the required pressure.



The lawn sprinkler is a form of water reaction turbine.

Turbines can also be made to work equally efficiently by using the *impulse* of the jet instead of the reaction. In practice, the two effects are very often used in combination. To carry the analogy of the garden hose a little further, it will be seen that the jet of water is capable of powerful direct action, such as knocking over a bucket or even breaking a pane of glass in the greenhouse (don't try this, please, unless you have some scrap panes to experiment on!). The idea of employing the impact force of steam to operate a turbine is a logical development, and the first recorded attempt to do so in a practical form was that of Giovanni Branca, in 1628. His engine employed a wheel with blades or paddles, on which steam impinged from a jet, supplied by some form of boiler, though this is not usually shown in the illustrations available. It was

proposed to use the power developed by the turbine, through reduction gearing, to drive a hammer mill, or battery of drop hammers, by projections on a rotating cylinder, which alternately engaged and released pawls on the hammer shafts.

Branca's engine could not have been very efficient, and it is very doubtful if it was ever put into practical use. It was not until a great deal more was known about the properties of steam, and also mechanical engineering generally, that it became possible to make a really efficient steam turbine; and even when this came to pass, its supremacy over its older rival, the reciprocating engine, was at first by no means decisive. At the present day, there are many purposes for which the latter is still preferred. For power on a really large scale, however, the turbine scores not only on account of its superior mechanical and thermal efficiency, but also its simplicity and ease of maintenance.

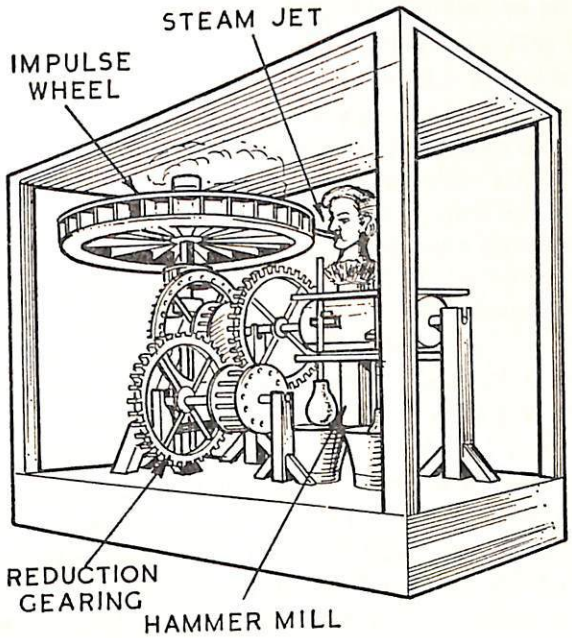
The early steam engineers were by no means unaware of the disadvantages and limitations of their cumbersome and slow-moving engines. At first, however, their brains and energies were fully occupied in improving the power and economy of these engines, and they were less concerned with making them more compact or running them at high speed. But soon it became apparent that a good deal of power is wasted in stopping and starting massive reciprocating parts at each stroke, and particularly when engines began to be used for generating electricity there arose a need for drastic changes in design.

Several of the pioneer steam engine designers, including James Watt, Richard Trevithick, and Richard Murdoch, visualised the possibilities of turbines and rotary engines. The principal obstacle to progress in the development of the turbine at that time was that, in order to make it efficient, it had to run at much greater speed than had ever been employed in engines before, and neither the metals, the manufacturing methods, nor the bearings and their lubrication, were equal to the task.

Steam at any appreciable pressure, on issuing from a jet, moves at a very high velocity, and in order to make good use of its kinetic energy, the blades of the turbine must also move at high speed. Here it is necessary to make distinction between *rotational* speed of the engine shaft and *peripheral* speed of the turbine rotor. The former refers to the number of turns the shaft makes in a

given time, and the latter to the distance in a linear path, as might be measured around the circumference of the rotor disc, at the radius of the jet stream. Both are high in a turbine, but the latter is influenced by the diameter of the rotor and will obviously be greater in a large turbine, for a given shaft speed, than it is in a small one. Rotational speed is measured in revolutions per minute (r.p.m.) and peripheral speed in feet per minute (f.p.m.). All turbines are therefore high-speed engines, and if not run at their designed speed, will lose efficiency and in some cases stall altogether, as the steam is capable of passing through them without being prevented from doing so by a close-fitting piston.

It was left to two engineers, working independently in two different countries at the latter end of the 19th century, to solve the problems of producing a really practical turbine. These were the Swedish engineer, Carl Gustav Patrik De Laval, whose turbine worked on the impulse principle, and the British engineer, Charles A. Parsons, who made a much more complex form of turbine which



A model of Branca's impulse turbine.

is generally referred to as a reaction turbine, though in fact both impulse and reaction forces are utilised with more or less equal effect. Both these turbines could be made to work with high efficiency, in terms of power in relation to steam consumption, and were very powerful for their size, but the Parsons turbine had the wider range of application, and has been the basis for most subsequent designs of impulse-reaction turbines which have been developed for all sorts of purposes, in sizes up to many thousands of horsepower.

CHAPTER II

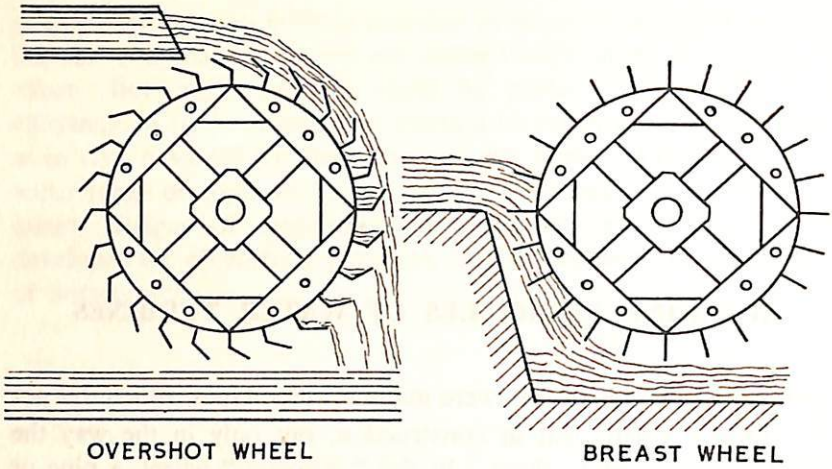
WORKING PRINCIPLES OF WATER TURBINES

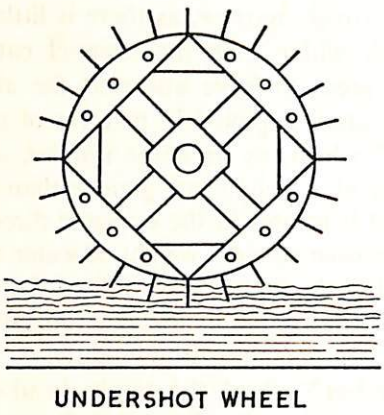
THE early water-wheels were made in three types, which did not differ a great deal in construction, but only in the way the water was applied to them. In the " overshot " wheel, a pipe or channel over the top of the wheel delivered the water at its highest point, and acted upon it for almost a complete half revolution. The power was derived mainly from the *weight* of the water, though the *kinetic* effect of fast-moving water striking the paddles of the wheel was also utilised to some extent. Such wheels were generally large in diameter and relatively narrow, as there is little to be gained by making them much wider than the channel carrying the water. Mills of this type seem to have attracted the attention of many artists, as they are often depicted in pictures of rustic scenes.

The " breast " wheel, as its name implies, accepts the water breast-high, that is, at a height not greater than about two-thirds of its diameter, and it rotates in the opposite direction to the overshot wheel. In this case also the weight of water accounts for most of the power developed ; the effective fall of the water is less, and it is generally made fairly wide, to take full advantage of broad streams without restricting their flow unduly.

In the " undershot " wheel, the gravity head of water is hardly utilised at all ; the wheel is simply mounted over a swiftly flowing stream so that only its paddles are immersed, and it works mainly by kinetic energy. Such wheels were mostly used where it was not convenient to build a dam or weir across the river to produce the necessary head of water to work other types of wheels, but a rapid flow of water was essential to make them work efficiently.

Water-wheels have been referred to in many old books on engineering and industry. Some of the earliest types were used





Three basic types of water wheels.

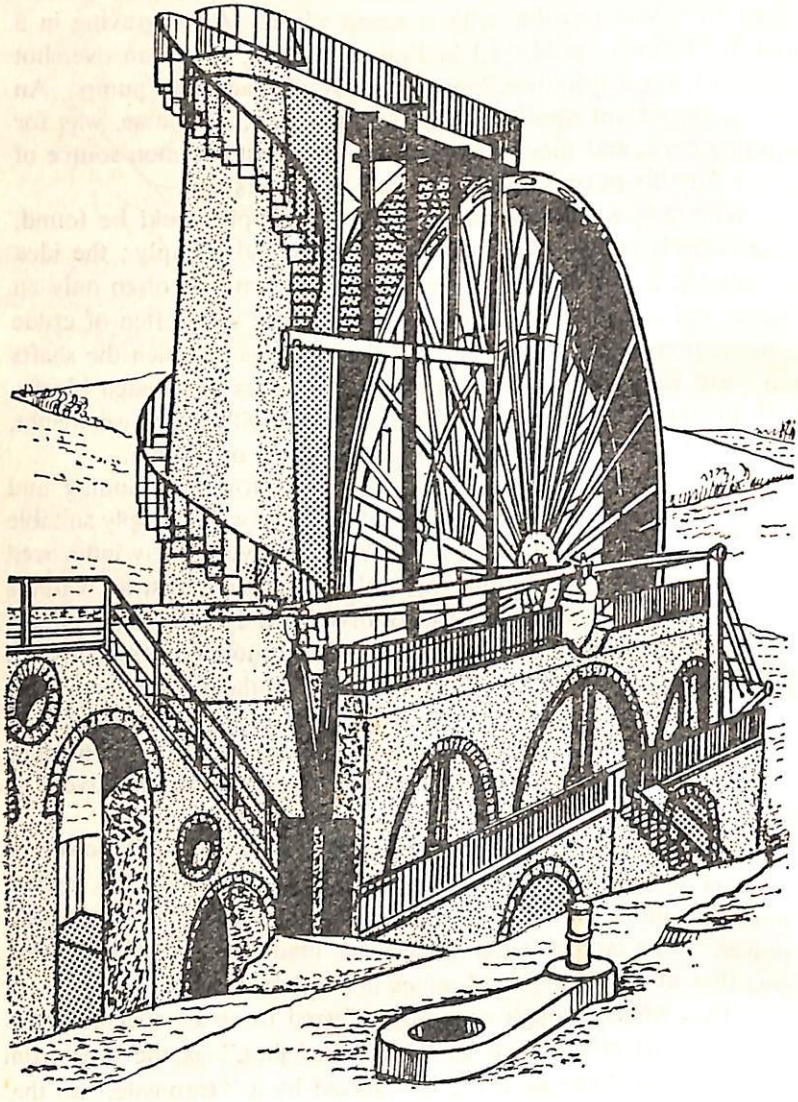
to lift water by means of scoops or buckets attached to the rim of the wheel. At a later date, chain pumps, or plunger pumps driven through cranks or beams, were used to lift water to much greater height than was possible with a scoop wheel. An engraving in a book by Ramelli, published in France in 1588, shows an overshot wheel driving a primitive form of rotary displacement pump. An equally important application of water-wheels, of course, was for grinding corn, and they were probably the most common source of power for this purpose until less than 100 years ago.

Wherever a suitable source of water supply could be found, water-wheels could be erected fairly easily and cheaply; the idea of building a mill house to accommodate them was often only an afterthought, even if it occurred at all. They were often of crude construction, mainly in wood, and the bearings in which the shafts ran were sometimes simply grooves or notches in wooden blocks, with no retaining caps, in which they rested with their own weight, lubricated mostly by the water which splashed over them.

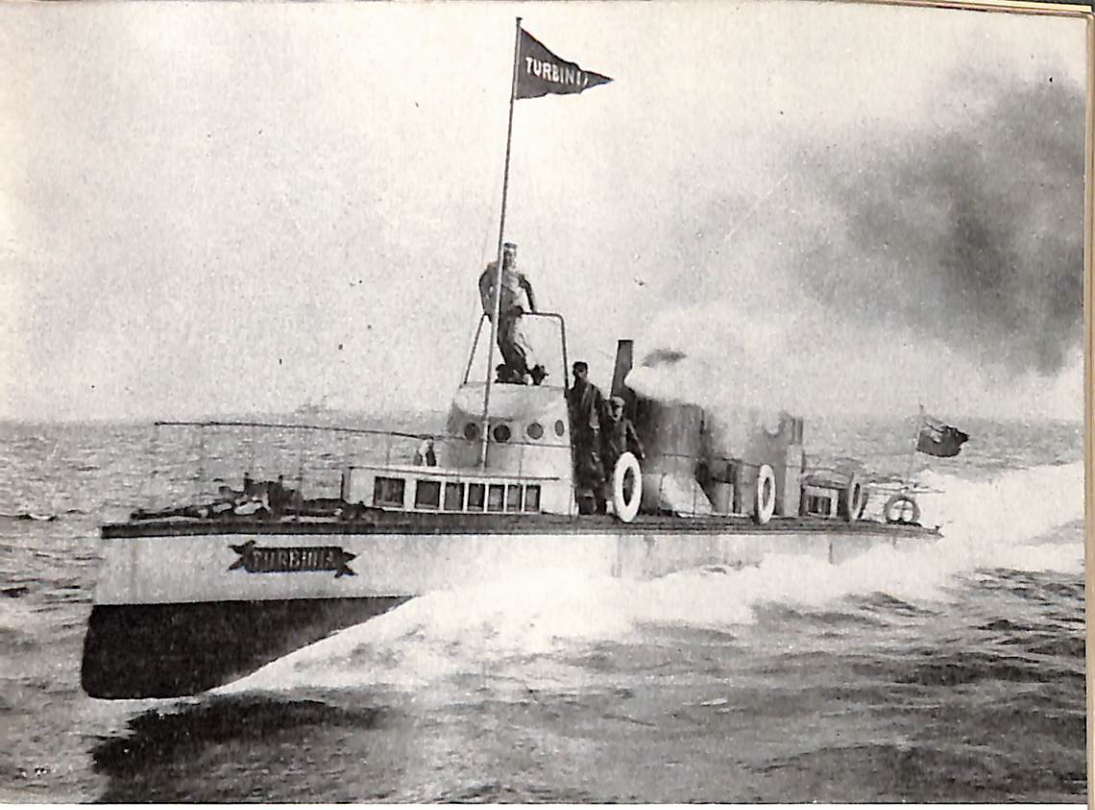
When machinery was first introduced for the spinning and weaving of textile materials, the availability of water supply suitable for driving mills in Lancashire and Yorkshire very likely influenced the selection of the localities for setting up these industries. Cutlers also used small water-wheels to drive grindstones, and miners whose workings were conveniently near mountain streams, in primeval regions of the world, often built similar wheels from local timber, and set them up to drive stamp mills, washers and separators for metal ores. Cornish tin mines also relied upon water power for drainage pumps, in the early days before the advent of steam engines.

Useful as these old mills undoubtedly were, their power in relation to size was relatively low, and soon reached the highest practical limits when widespread demands arose for industrial power. The largest water-wheel ever made, so far as is known, was that at the Laxey lead mines in the Isle of Man.

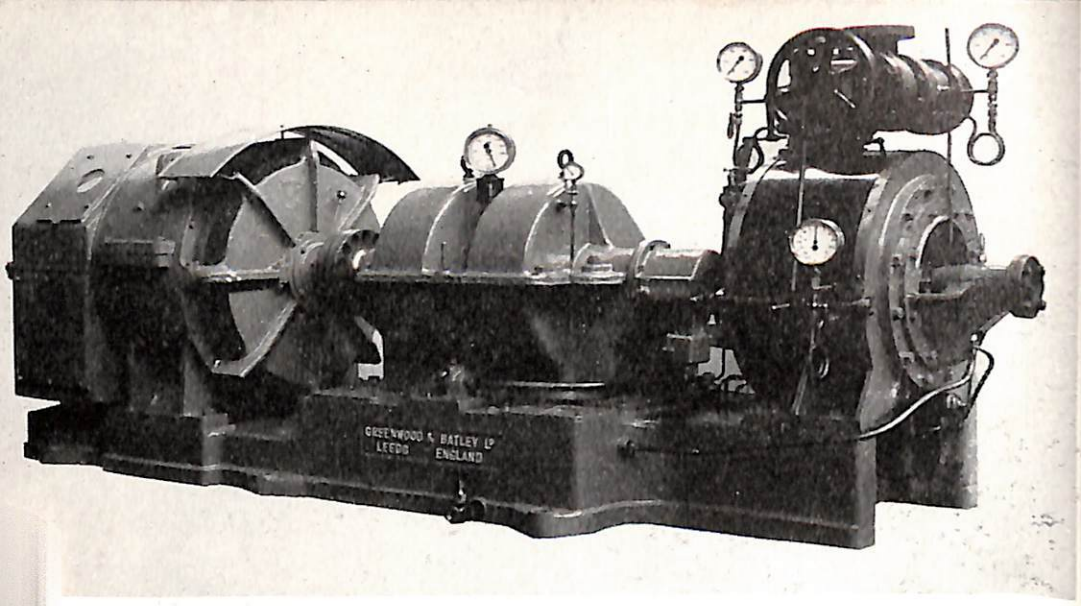
This wheel, though generally referred to as an overshot type, is more correctly known as "pitch-backshot," as the flow from the overhead flume or chute is reversed by a "trap-gate," so that the wheel rotates in what might appear to be the wrong direction. The object of this is to enable the wheel to be shrouded by a casing built out from the tower, to prevent water blowing out of the

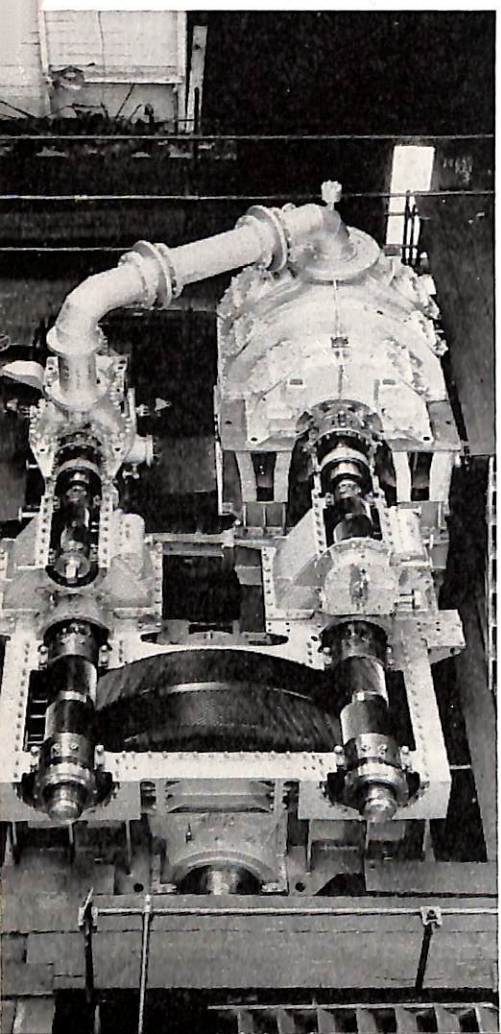


The Laxey " Lady Isabella " water-wheel.

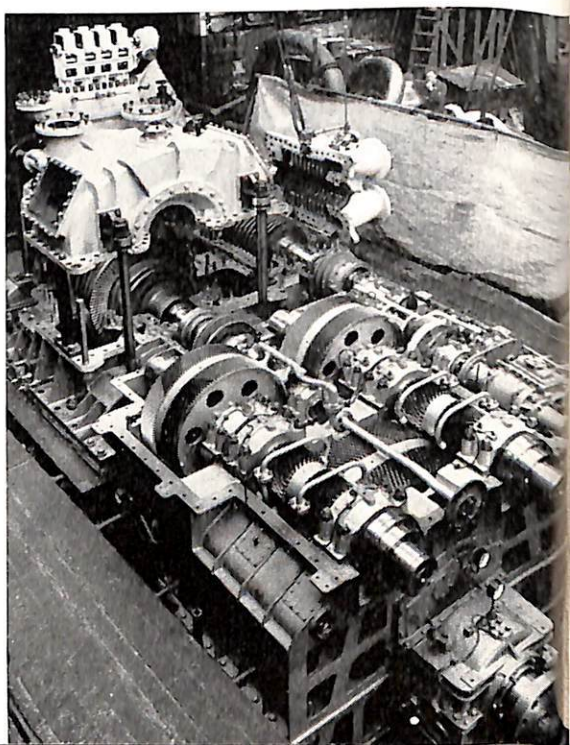


(*Above*) S.Y. *Turbinia*, the first turbine-driven ship, steaming at 34 knots. (*Below*) How the turbine grew in 13 years; *Turbinia* (1894) alongside R.M.S. *Mauretania* (1907).





(*Above*) A modern de Laval type impulse turbine and gear-driven generator by Greenwood and Batley Ltd. (*Below*) A set of geared turbines (upper casings removed) for frigate H.M.S. *Grafton*. (Richardsons-Westgarth Group). (*Left*) The turbines for T.S.S. *Funchal* (twin-screw, 6,123 h.p. per shaft at 150 r.p.m., speed of vessel 21½ knots). (Richardsons-Westgarth Group).



buckets in high winds. Springs on the slopes of Snaefell, the highest point on the island, supply water at an ample head to the tower through 600 yards of cast iron pipes.

Known as the "Lady Isabella," the wheel was first put to work in 1854, and had an active life of over 75 years, pumping water from a depth of 200 fathoms (1,200 ft.) at the rate of 250 gallons per minute, equivalent to nearly 200 h.p. This was terminated, not by the failure of the wheel, but by the closing down of the mines. The diameter of the wheel is 72 ft. and the breadth of the buckets 6 ft.

Although this wheel was a monumental work of engineering, and achieved its purpose admirably, it is interesting to observe, in the light of later knowledge on water turbines, that a Pelton wheel of no more than 8 or 9 feet diameter, working at the same head of water, would produce the same power, without the need for erecting the huge tower and other external buildings. But like most other modern engineering works, it would then have remained unseen and largely unappreciated, instead of becoming the impressive spectacle which still remains for all to see.

The inability of open wheels to make the most efficient use of falls or "heads" of water much greater than their own diameter led to the development of the modern forms of water turbines. These are capable of utilising much greater heads and velocity of water, and work on either reaction or impulse principles, or both combined. The classification of these turbines is somewhat vague, as they are often referred to as "low" or "high" pressure types, but these terms are purely relative. Although some types will work at heads comparable with those used for the old water-wheels, much greater heads, with proportionate increase of power, are usually employed, and the high pressure types very frequently work at a head of several hundred feet.

To explain the effects of head, pressure and velocity, a brief review of the basic principles of hydraulics is worth while. A cubic foot of water weighs 62.5 lb. if fresh (sea water is approximately 64 lb. per cu. ft.) and a column of fresh water 1 ft. high in a vertical vessel or tube of 1 sq. in. cross sectional area, will produce a pressure of 0.43 lb. at its lowest point, due to the weight of water contained in it. By increasing the height of the column, the pressure becomes proportionately greater, and the terms "head" (expressed

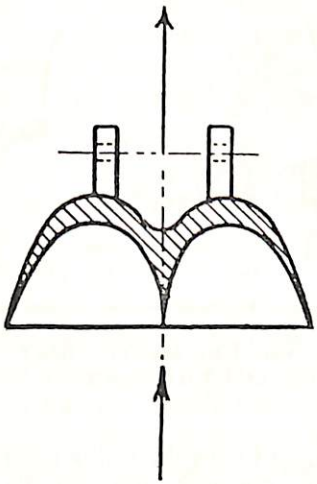
in feet) and pressure (in lb. per sq. in.) are directly related. A column of water 100 feet high, no matter what is the size or shape of the reservoir, channel or pipe, will produce 43 lb. pressure on every square inch at the bottom.

If the water is allowed to flow down a pipe or over a waterfall from a height, its pressure will be converted into velocity, through acceleration due to gravity, though its weight remains unchanged. For the sake of exactness, it may be stated that acceleration is the rate at which the velocity of a moving body increases in relation to time. Kinetic energy is the energy stored in a moving body, by reason of its weight, velocity and gravitational acceleration expressed by the formula $\frac{WV^2}{2g}$. But in practice acceleration is influenced by fluid friction due to the shape of the passage or orifice through which the fluid flows, and also by its viscosity, or natural sluggishness, which tends to make it cling to the sides of the passage. Water, petrol or alcohol will obviously flow more freely than thick oil or treacle, quite apart from their weight or specific gravity. These simple rules hold good for all gaseous and liquid fluids, and affect the performance of all kinds of turbines.

The impulse or "high pressure" form of water turbine is perhaps the easiest to understand, at least in its basic principles, because it simply employs a jet or nozzle through which water is directed tangentially on to a wheel which is fundamentally similar to the old type of water-wheel. In fact, many impulse water turbines have employed wheels with flat radial or slightly concave blades or paddles, but they are not highly efficient, for reasons which are quite easy to understand. If a jet of water is directed at right angles on to a flat plate, only its immediate impact can be employed usefully, as the water which splashes off in all directions still contains much of its kinetic energy, which is therefore wasted. To obtain the maximum efficiency, it is necessary to shape the blades of the turbine in such a way that splashing is eliminated, so that the jet is practically turned back on itself, and leaves the wheel with little or no energy left in it. In other words, the jet "follows through," and continues to exert force on the wheel after its initial impact.

A very simple experiment will illustrate how this principle operates. Take a tea mug or other flat-bottomed vessel, and direct water into it from a tap, preferably with a nozzle to concentrate

the flow. (This experiment should be conducted in the bathroom or scullery, where a few splashes will not be objected to!) The water, when it strikes the bottom of the vessel, will splash backwards with appreciable force, but little sense of direction. Now repeat the experiment with a teacup or a ladle of more or less hemispherical internal shape. If the water is directed into the centre of it, the result will be much the same as before; but if the jet is directed near one side, the turbulence of the water will greatly decrease, and it will rebound in a more ordered flow, almost in the opposite direction. This establishes how important is the shape of the paddles, buckets, vanes or blades (as they are variously called) in any kind of turbine, whatever fluid is used to drive it.

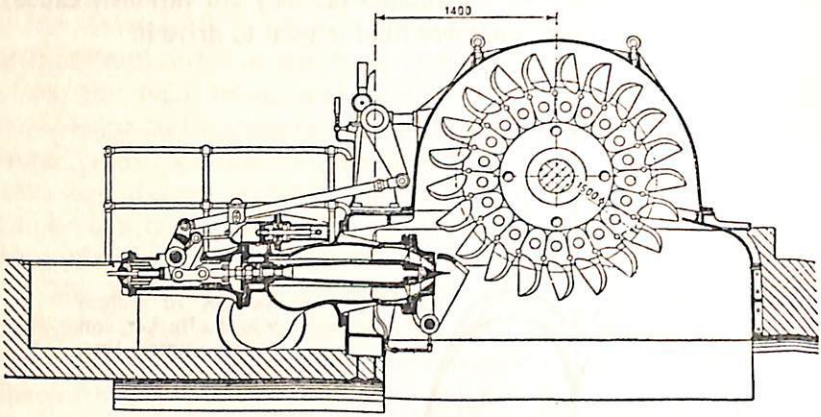


Section of Pelton wheel bucket on radial centre line.

One of the first high pressure water turbines was invented by Pelton, who found out by accident how efficiency was affected by the shape of the buckets and the disposition of the jet. His early turbines had a number of hemispherical buckets fixed around the edge of a disc wheel, with the jet directed tangentially into their centre. On one occasion the wheel in some way became moved endwise, so that the jet entered near the edge of the buckets, and it was found that under these conditions the wheel ran faster and developed more power. But the displacement caused undesirable end thrust on the shaft, so at first tests were made with the buckets

mounted off centre to each side, or in other words "staggered" alternately; in this way the end thrust was balanced. Later it was found better still to make the buckets in the form of double hemispheres, with the jet directed on the sharp dividing edge between them. This type of bucket became accepted for general use, and was further improved in detail by other designers, including S. A. Berry and W. A. Doble.

The number of buckets on the wheel is also important; if too few, they allow the jet of water to escape between them, and if too



Sectional elevation of a Pelton wheel by Messrs. Escher Weiss, developing 4,200 h.p. at 1,310 ft. head.

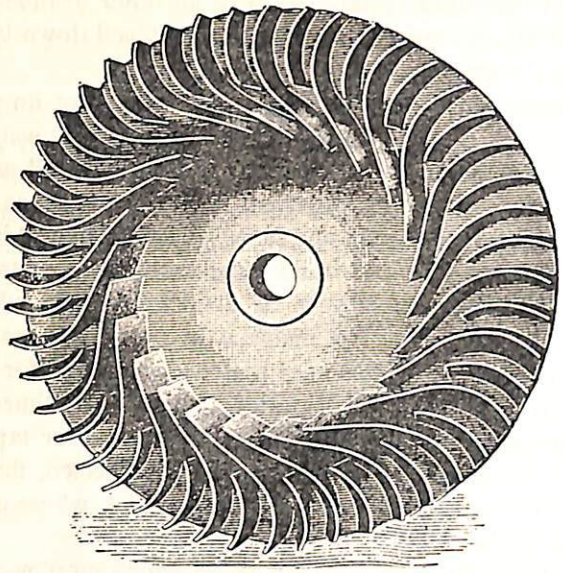
many, they get in each other's way, so to speak, as the return flow from one bucket strikes the back of the next, and actually has a retarding effect. There is no definite rule for the number of buckets, as their size in relation to the diameter of the wheel varies widely; not less than twelve are usually employed. The shape of the jet nozzle is also highly important, in order to reduce fluid friction and ensure the highest possible velocity at the jet. It is usual to locate the nozzle at a tangent to the radial centre of the buckets, and more or less horizontally on the underside of the wheel, so that the water is not carried round more than necessary. So well are the details of jet and wheel design carried out in some of these turbines that, when in action, the water jet looks like a solid glass rod, and the exhausted water falls almost vertically with little

energy left in it ; and they will attain efficiency of over 90 per cent. when run at optimum speed. As with all other turbines, they lose efficiency at an increasing rate if they are slowed down by overload or faults in design.

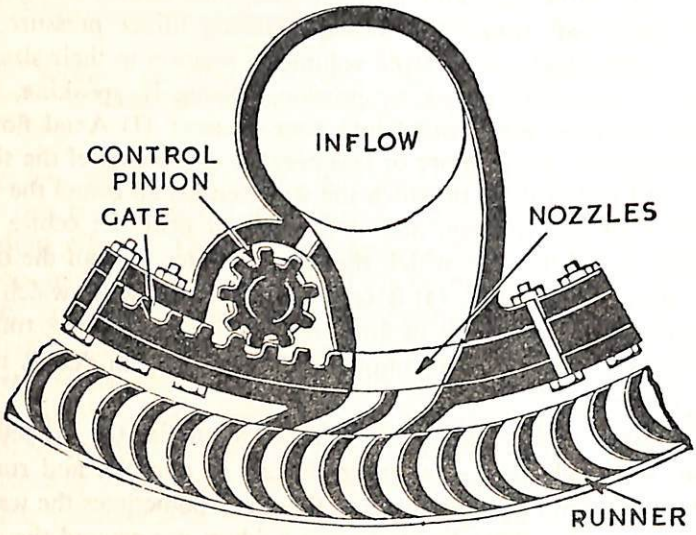
An advantage of the Pelton or similar type of impulse wheel for working at a considerable head is that the water can be conveyed to it through a pipe of relatively small size, which greatly reduces the work involved in installing it, as compared to turbines of lower velocity and large volume, where it is necessary to excavate the ground and build large channels of metal, masonry or concrete. Where a supply of artificially-produced hydraulic pressure is available, as for instance in naval gun turrets, small Pelton wheels are sometimes used to drive generators for emergency lighting. At one time small water motors, sometimes crude in design, were sold for working from domestic water taps, claimed to produce " free power," but as might be expected, these did not long escape the notice of waterworks authorities, whose disapproval led to their withdrawal.

Other types of turbines than those which employ an impulse jet are generally more suitable for working at lower heads of water, though this does not hold good in all cases, especially when they are of very large size and power. They are usually designed to accept water all round the wheel, utilising direct pressure, and therefore can deal with a large volume in relation to their size, and produce power in similar proportion. Roughly speaking, these turbines may be sub-divided into four classes: (1) Axial flow, in which the water flows more or less parallel to the axis of the shaft: (2) Inward radial-flow, in which the water enters all round the outer periphery of the turbine, and is discharged near the centre : (3) Outward radial-flow, in which the flow of water is from the centre to the outer periphery : (4) Mixed or diagonal flow, in which both axial and radial directions of flow are combined. All these turbines have certain features in common, and differ only in details rather than principles.

In Class 1, the rotor of the turbine resembles the propeller of a ship, with helical blades, generally few in number, and running in a tunnel with a fine clearance at the tips. Sometimes the water is guided into the turbine by stationary guide vanes around the entry, and in other cases by a channel or " flume " of special shape. One



Inward radial-flow vortex turbine wheel.



Part sectional plan view of an outward radial-flow Girard turbine showing sluice gate control gear.

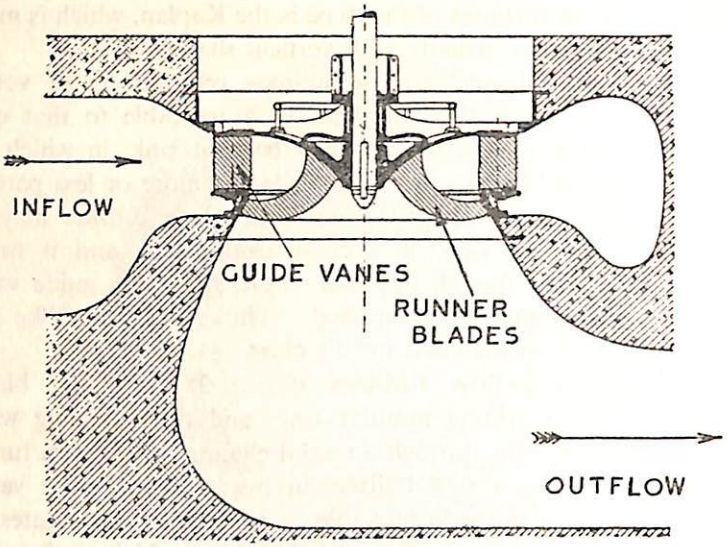
of the best known turbines of this type is the Kaplan, which is made up to very large sizes, usually with vertical shafts.

Turbines in Class 2 are sometimes referred to as vortex turbines, as the water flow in them is comparable to that of a whirlpool, or the free outflow from a bath or sink, in which the water is set in rapid rotation. The blades lie more or less parallel to the axis and vary widely in number. This turbine may be described as an inversion of a centrifugal pump, and it works largely by reaction, though in cases where stationary guide vanes are fitted, direct impulse is applied. The Thomson, Gilke and Francis turbines are included in this class.

Outward radial-flow turbines (Class 3) have the blades arranged in an overhung annular ring, and the inflowing water enters at the open end through an axial channel. It is then turned at right angles into a radial direction by means of guide vanes, which are sometimes made movable or fitted with sluice gates for the purpose of control. In the Girard turbine, which conforms to this class, the water does not enter all round the ring of blades, but through a number of equally spaced gates or nozzles which are individually controllable. These turbines are comparable to impulse turbines with multiple jets, though the water velocity is lower than in the Pelton wheel, and the volume a good deal greater.

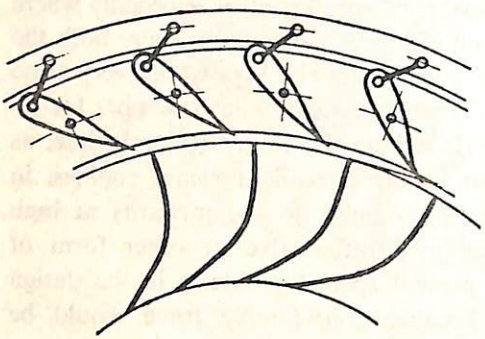
Mixed flow turbines (Class 4), are mostly modifications of the two former classes, and their main object is to avoid losses which occur in changing the direction of the flow of water abruptly at right angles, which is a practical necessity in many installations. In the design of all kinds of turbines, it is essential to promote smooth flow in all passages, and the curvature, angle and cross-section of the blades are all a part of this scheme.

All turbines must be capable of speed control, especially where they are employed for driving electrical generators, where both the voltage and frequency of the supply must be kept within very close limits, irrespective of load demands. Automatic governors for all kinds of engines are mostly based on the centrifugal principle, as first applied by James Watt to the control of steam engines, in which the tendency of rotating weights to fly outwards at high speed is utilised to operate a throttle valve or other form of regulator. Water turbines present special problems in the design of the regulating device, because considerable force would be



Sectional elevation of a vertical-shaft mixed flow Francis turbine.

necessary to move a throttle valve against high pressure and weight of water. In the case of the Pelton wheel, the governor sometimes acts by diverting the angle of the jet, or splitting it by means of a cone inside the nozzle. Movement of the guide vanes or runner blades, which may be pivoted at their centre of pressure balance to reduce the effort required, is the method commonly employed in other turbines.



Part plan view of Francis turbine showing movable control vanes.

Chapter III

THE EVOLUTION OF THE STEAM TURBINE

IT has been explained that in any form of turbine, kinetic energy is utilised as the motive force, and that in order to employ it efficiently, the turbine must run at a peripheral speed which bears some relation to the speed of the working fluid. Water or other liquid, owing to its weight, produces very high kinetic energy at moderate velocity, but air, steam or gaseous fluids are light and tenuous, so that only when moving at extremely high velocity can they exert useful force on a turbine, which must therefore move at a correspondingly high speed.

There is no difficulty in obtaining high velocity with these fluids, especially when jets specially designed for this purpose are employed. The major problem is how to apply it effectively to the turbine. Early attempts to produce a practical steam turbine were hampered by the fact that the need for very high speed was not fully realised, and the means to make use of it were not available. The orthodox steam engines of the early industrial era were slow and ponderous; 20 to 30 r.p.m. were considered quite fast for rotative beam engines, and when direct-acting engines were introduced, few of them ran at more than 100 r.p.m. Marine engines driving screw propellers were run at not more than 80 to 90 r.p.m. until well after the beginning of the twentieth century, though naval engineers, under the spur of necessity in destroyers and other fast craft, dared to force them up to as much as three times this speed. When steam engines were first applied to generating electricity, and higher speeds became highly desirable, the enclosed engines by Willans and Westinghouse were regarded as highly dangerous by many people, with their terrifying speed of 400 to 500 r.p.m.

The difficulty of transmitting power from an engine running at very high speed was a further obstacle to the development of

the steam turbine. The design and construction of toothed gearing was in its infancy, and such gearing as was used on industrial machinery was crude and inefficient, suitable only for slow speeds. It took nearly 100 years of constant effort by machine tool designers, from Maudslay onwards, to produce machines capable of generating gear teeth accurately. In many applications of turbines to-day, gearing is necessary for the transmission of power, and has a vital influence on the overall efficiency of the plant.

An early attempt to employ a reaction turbine for practical purposes is shown in the patent of Wolfgang de Kempelen, dated 1784. His engine was basically a modification of Hero's Aeolipile, having a horizontal tube closed at both ends, and mounted by its centre on a hollow pivot, which formed the steam entry from the boiler. Small holes were drilled in opposite sides of the tube, near the closed ends, and formed tangential jets from which reaction was produced by the escaping steam. A bevel gear fixed to the centre of the tube was used to transmit power, but no attempt was made to employ it as a reduction gear.

A turbine of this type, if run at an efficient speed, would probably reach bursting point, especially if only slightly out of balance. Apart from mechanical faults, it would be most undesirable to allow steam to escape from open jets in all directions. A more practical approach to the problem was shown in the patent of 1849, by Nasmyth, who, incidentally, was also the inventor of the steam hammer. This took the form of a hollow disc having four curved tangential passages which formed reaction jets, and enclosed in a casing with an exit pipe for exhaust steam. It was used to drive a circular saw mounted directly on the outer end of its shaft, and was reputedly successful, though probably not very economical in steam consumption. A somewhat similar arrangement, though the rotor was of "swastika" form with four arms like those of Hero's turbine, was used for driving a fan blower, a duty for which its high speed and relatively low torque were well suited.

The rotary engine patented by James Watt, though often referred to as a turbine, was really a combination of displacement engine and water turbine, in which steam pressure was employed to displace water alternately from compartments of a rotating vessel, the outlets from which formed water reaction jets.

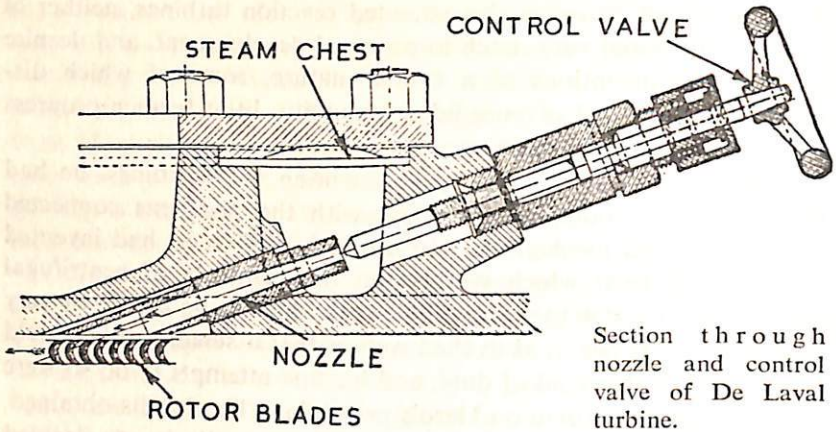
Trevithick and Ericsson also patented reaction turbines, neither of which contributed very much to practical development, and despite many other inventions of a similar nature, some of which displayed a good deal of misguided ingenuity, little further progress was made for many years.

When De Laval started experimenting with turbines, he had already been brought into contact with the problems connected with high speed mechanism. In the early 1880's, he had invented cream separators, which worked on the principle of centrifugal force, and in order to operate efficiently, had to be driven at very high speed. It occurred to the inventor that a steam turbine could be applied to this kind of duty, and his first attempts to do so were with a reaction turbine on Hero's principle. The results obtained, however, were rather disappointing, and eventually it was decided that an impulse turbine, basically similar to a Pelton wheel, would be more suitable.

For various reasons, the Pelton wheel, in the form made to work with a water jet, is not capable of working efficiently on steam. In the first place, the much lower density of steam reduces the kinetic energy at a given velocity, and therefore lowers the impact force on individual buckets. These must therefore be considerably increased in number, and set much closer together. It is also necessary to modify the form of the jet nozzle and set it much closer to the wheel. De Laval therefore discarded the peripheral position of the nozzle, and located it at the side of the wheel at an acute angle, almost touching it. The blades were made crescent-shaped, so that the spaces between them formed steam passages which deflected the passage of the steam, causing it to emerge from them at an angle opposite to that of entry.

Instead of the convergent angle of nozzle employed in a water turbine (i.e. tapering down towards the discharge end) the nozzle of the De Laval turbine first contracts down to a narrow throat and then diverges towards the orifice. This type of orifice converts the pressure of the steam (which, unlike water, is an *expansible* fluid) into velocity, so that when it enters the blades of the turbine, practically all the energy in it is *kinetic* energy.

In order to take full advantage of this energy, the turbine wheel should run at a peripheral speed bearing a definite relation to the velocity of the steam. With the jet disposed at 20 degrees to the



Section through nozzle and control valve of De Laval turbine.

side of the wheel, the peripheral speed, measured at the radius of the blade centre, should theoretically be 34 per cent. of the steam velocity. For instance, if the latter is 4,000 feet per second, the peripheral speed should be 1,360 feet per second, and a corresponding percentage of the kinetic energy in the steam jet thereby converted into useful work. This figure is not reached in practice, due to mechanical and fluid friction losses, and therefore the efficiency of the turbine, in terms of horsepower in relation to steam consumption, is not as high as it should be, especially in the small sizes, where it is very difficult to run the turbine at the rotational speed comparable with the required peripheral speed. It may, however, compare very favourably with the efficiency of reciprocating steam engines, in which, besides mechanical losses, considerable heat losses also occur.

In tests of De Laval turbines made some years ago, it was found that a wheel of 4 in. effective diameter, running at 30,000 r.p.m. and peripheral speed of only 515 f.p.m., produced 5 horsepower. A 30 in. wheel running at 10,600 r.p.m. was able to use a much higher peripheral speed, 1,378 f.p.m., and produced 300 horsepower. It is therefore an advantage to use relatively large wheels, as they can be run at manageable speeds, but in view of the considerable power of these turbines in relation to their size, it is not always practicable or convenient to make them large when only moderate power is required.

One of the practical problems in any machines which run at very high speed is the balancing of the rotating parts, so that they run with little or no vibration. A small unbalanced weight which may have no noticeable effect at a few hundred r.p.m. will cause violent vibration, capable of wrecking a machine, or at least destroying its bearings, when the speed is multiplied from 20 to 50 times. Turbine wheels must always be balanced as meticulously as is humanly possible, and precision machines which detect very minute errors in either static or dynamic balance have been developed; but sometimes, even with their aid, the results obtained fall short of perfection. De Laval overcame his difficulties in this respect by making the turbine shaft slightly flexible, so that it was capable of finding its own balance, and any slight unbalanced forces were not transmitted to the bearings or the frame of the machine, in the form of vibration.

The centrifugal forces in the turbine wheel are also extremely high, and a badly designed wheel, or one of unsuitable material would be liable to burst at high speed. Even drilling a central hole to mount the wheel on its shaft may weaken it to an undesirable extent, and the larger sizes of De Laval wheels are therefore made with solid centres, attached to flanged half-shafts by bolts. The attachment of the turbine blades, in cases where they are not machined from the solid, is equally important, and many ingenious methods of securing them have been devised for De Laval and other turbines. In many cases a shroud ring is fitted over the outside of the blades.

Extraction of the exhaust steam from the turbine casing, after it has done its work on the blades, is usually assisted by leading it to a condenser, in which rapid cooling takes place, creating a vacuum by the decrease of volume as the steam is reconverted into water. This not only increases the effective range of working pressure, but also reduces the fluid friction on the turbine wheel and enables it to run more freely. Back pressure in the casing slows up and reduces the efficiency of all kinds of turbines, and condensing plant is usually regarded as an essential part of their equipment. Reduction gearing is necessary to enable the power of the turbine to be usefully applied to most practical purposes, except possibly separators, centrifuges and fan blowers. To enable the maximum power to be obtained from a De Laval turbine, it

is often fitted with several nozzles, and these may be individually controlled by stop valves, operated either manually or by an automatic governor.

A totally different approach to the turbine problem was made by the Hon. C. A. Parsons, whose father, the Earl of Rosse, was a world-famous astronomer and a designer of a very successful reflecting telescope. Parsons himself also made important contributions to this work and the firm which he founded is still noted for the manufacture of reflecting mirrors for telescopes and searchlights. In 1872 he went to Dublin University, and later to Cambridge, studying mathematics and physics. His practical training began in 1877, at the Elswick works of Messrs. Armstrong, and four years later he became a junior partner in the firm of Messrs. Clarke, Chapman & Company, at Gateshead, near Newcastle upon Tyne.

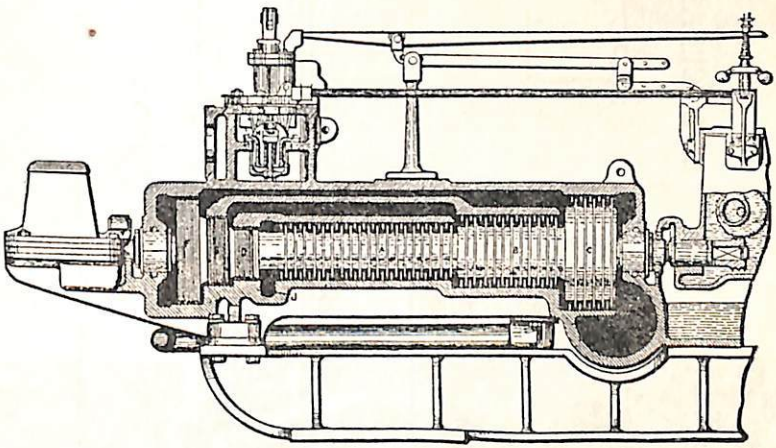
At that time many expert engineers regarded the turbine as an inventor's pipe dream, which could never be more than a toy. Parsons thought differently, and embarked on a series of experiments which, after many disappointments and setbacks, culminated in the most efficient engine ever invented up to that date. Although he had the most up-to-date facilities available for building high-speed machinery, he decided that in order to make the turbine applicable to general work, it would be necessary to make it run efficiently at a lower rate of rotation than had hitherto been possible.

To do this he proposed to use a multiple form of turbine, in which the steam was expanded in a number of pressure stages, instead of being converted into kinetic energy in a nozzle. In this way, although each stage would run at lower efficiency, and contribute only a small amount of power, the aggregate effect would be great and the efficiency high, with a speed much lower than that of the single-wheel impulse or reaction turbine.

The first Parsons turbine, built in 1884, did not realise these aims; it developed 5 h.p. at 18,000 r.p.m. and was direct-coupled to a $7\frac{1}{2}$ kW. dynamo. It was very compact and smooth running, but had a very high steam consumption, so that it could not be regarded as a serious competitor to the existing types of reciprocating engines, some of which, by careful design, had achieved a high degree of economy. But within a few years, Parsons succeeded in improving the turbine to such an extent that it

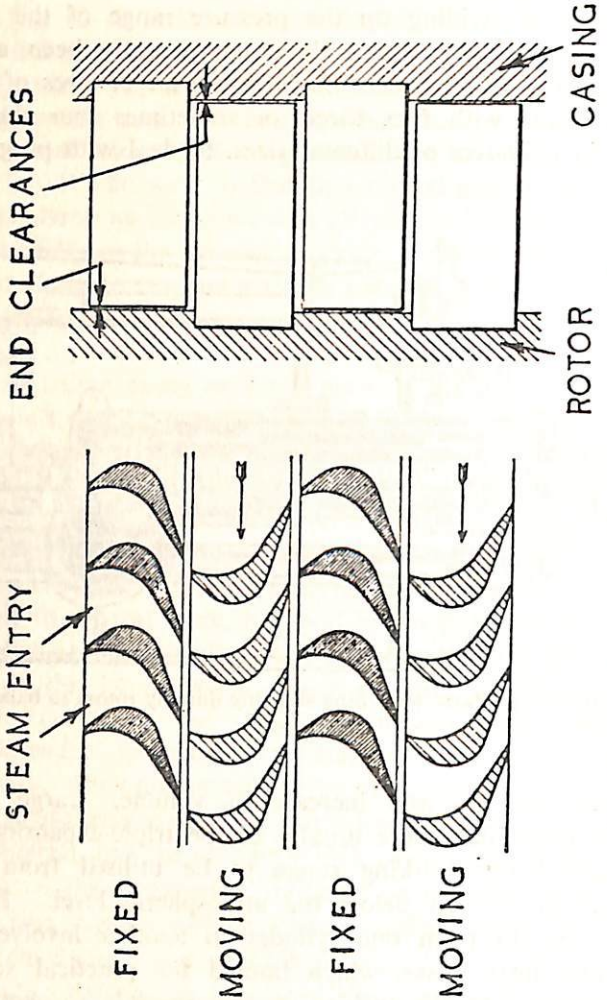
could compete with these engines on equal terms for such purposes as generating electricity. It was his ambition, however, to extend its application to many other duties, including the propulsion of ships.

The idea of dividing up the pressure range of the steam, or "compounding" as it is called, had already been applied successfully to ordinary steam engines, the larger sizes of which were often made with two, three, or sometimes four stages of expansion, in cylinders of different sizes, to deal with progressive

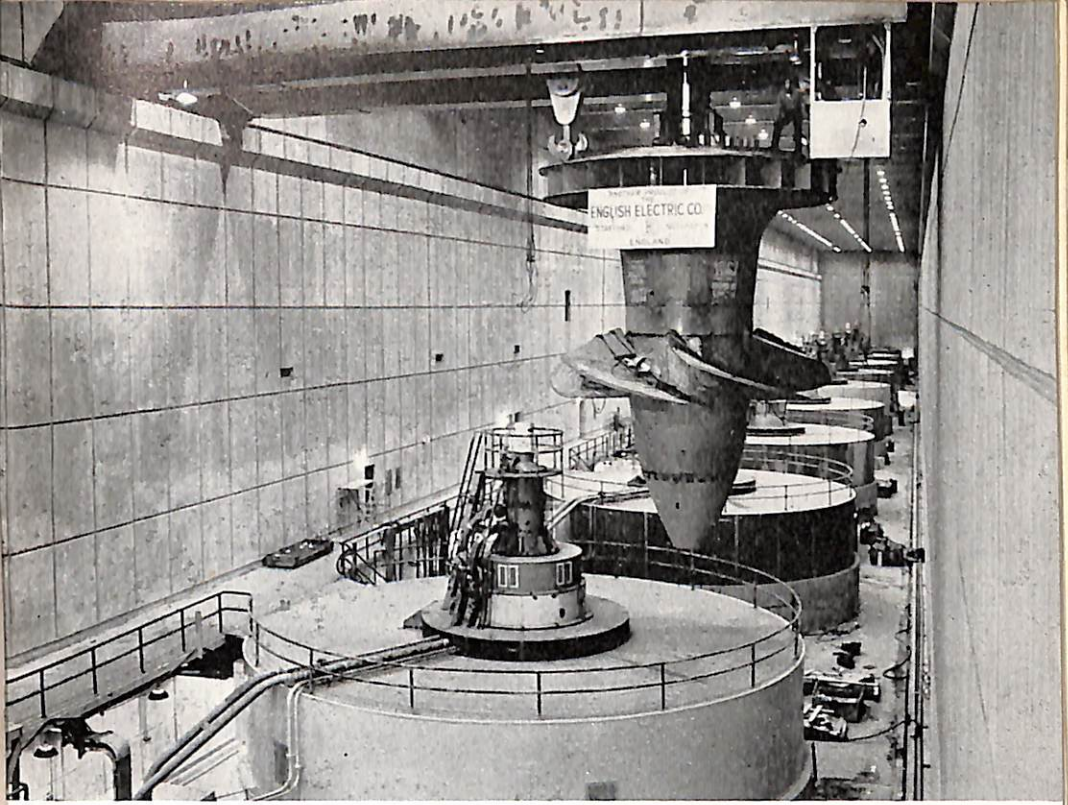


Early three-stage Parsons turbine showing dummy rotors to balance end thrust.

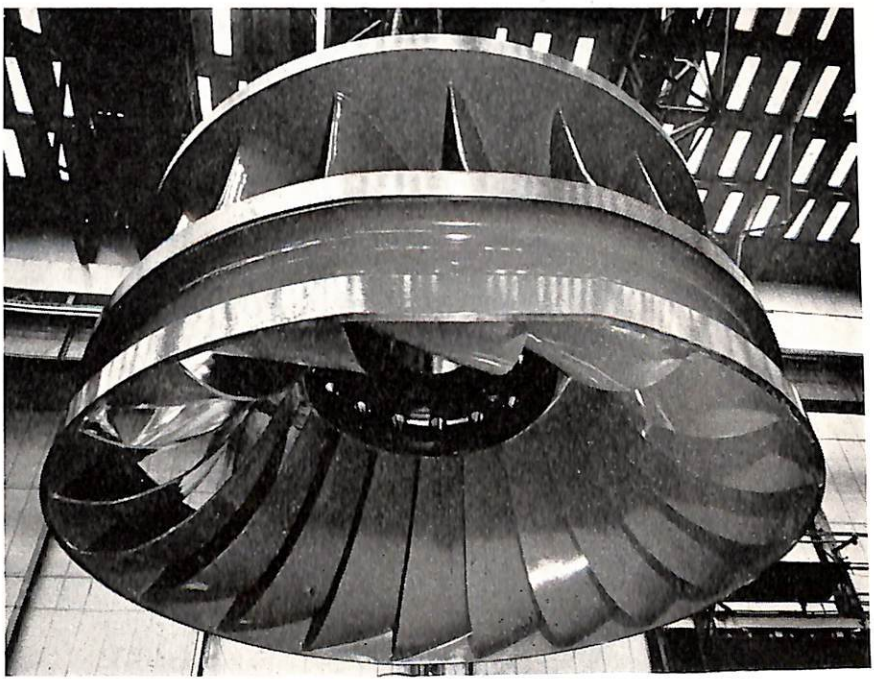
lowering of pressure and increase of volume. Large marine engines, in particular, were usually of the triple-expansion type, which enabled the working range to be utilised from boiler pressure down to well below the atmospheric level. But the transfer of steam from one cylinder to another involved both pressure and heat losses, which limited the practical value of these measures. In the turbine, it was possible to carry compounding much further in a single "cylinder" or working chamber, by increasing the number of sets of blades and progressively increasing the size of the blades. In addition, heat losses were still further reduced by the unidirectional flow of steam from the hot to the cool end.



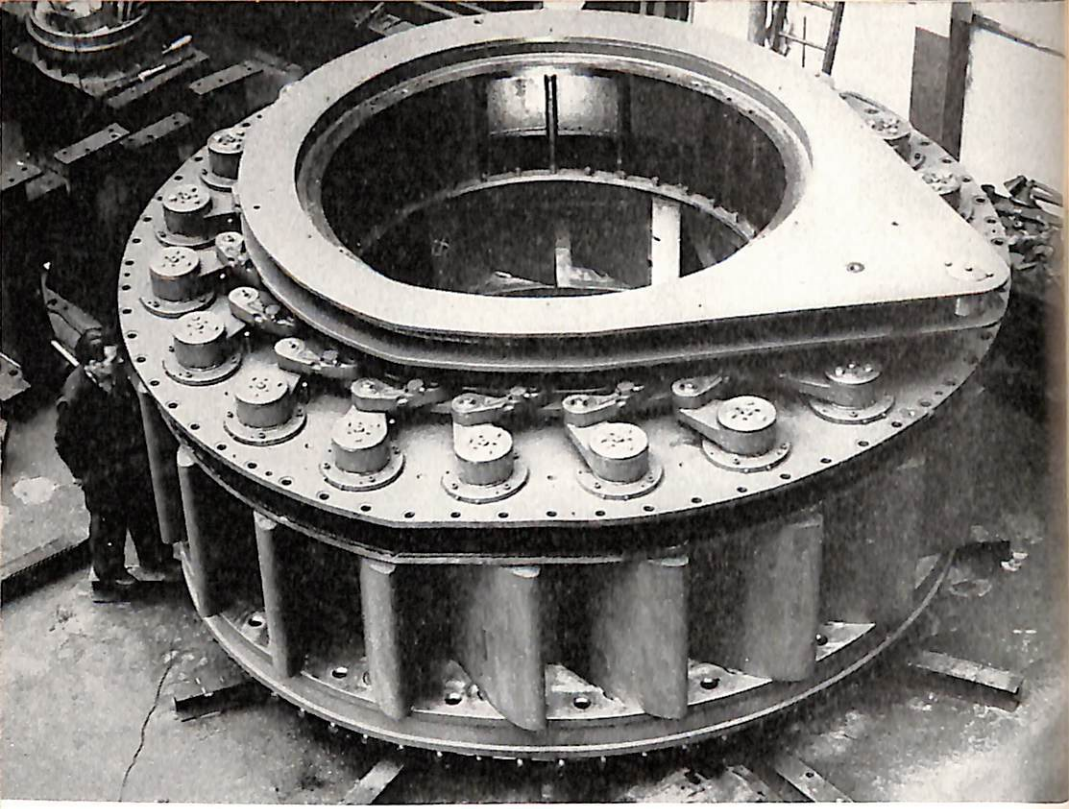
Arrangement of fixed and moving blades in Parsons' turbine.



Runner for 131,000 h.p. Kaplan turbine for Priest Rapids power station (English Electric).

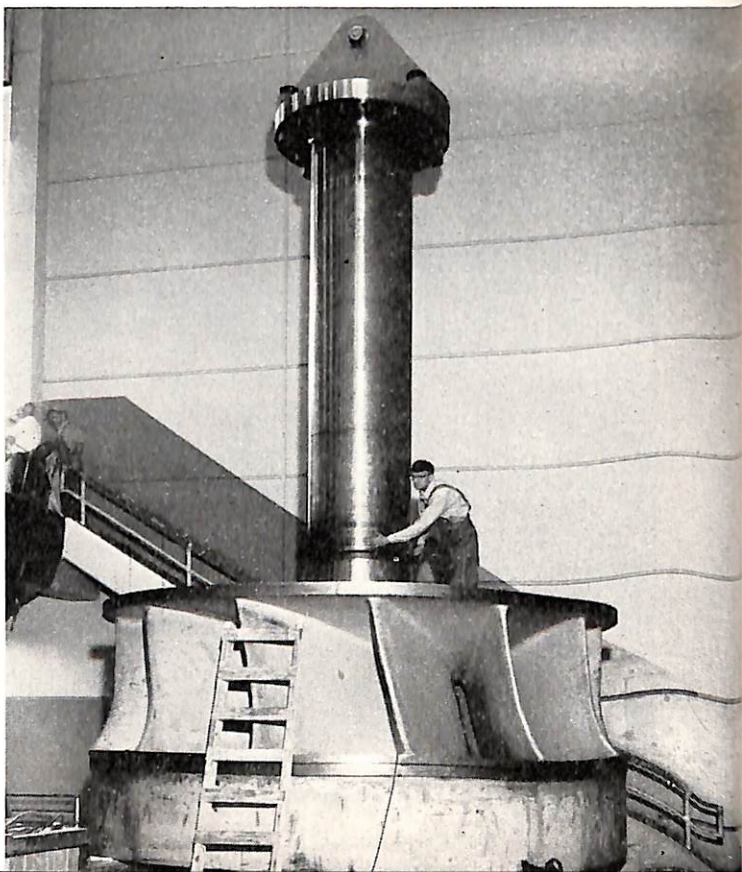


Runner for Francis turbine at Kariba power station (Boving & Co. Ltd.).



(*Above*) Guide vanes and control gear for Francis turbine at Catagunya (Boving & Co. Ltd.).

(*Right*) Runner for Francis turbine at Table Rock, U.S.A. (English Electric).



In the Parsons turbine, no nozzles are employed; the steam is admitted all round the circumference at the admission end of the casing, but before encountering the first stage of rotor blades, it passes through a row of stationary blades, the shape and angle of which direct it in such a way as to operate to the best advantage. From then onwards, the steam passes through alternate rows of rotor and stator blades, losing a little of its pressure at each stage until it is released at the exhaust end to a high vacuum. Parsons was the first to employ the vacuum produced by the condenser to increase the power of a turbine by a substantial amount.

The development of the parallel or axial flow turbine over a period of several years proved a costly business, and at times Parsons was seriously embarrassed for financial resources. Until the turbine could be exploited successfully in commercial production, the value of his patents was somewhat dubious, because most of their theoretical details had been anticipated to some extent by previous inventors. He patented other forms of turbines, including some in which the steam was expanded in a series of radial stages, from the axis outwards to the circumference of a rotor disc. But the reward for his labours came when he developed a successful marine turbine and was able in 1894, to patent the application of steam turbines to marine propulsion. Henceforth, until the expiry of these patents, anyone who wished to use a turbine of any make to drive a ship could only do so under licence from the Parsons Marine Steam Turbine Company.

After many experiments with models, the company built a steel vessel 100 feet long, with a displacement of 44 tons, having a water-tube boiler generating steam at 210 p.s.i., and a turbine of the multiple radial flow type, developing 960 h.p. at 2,400 r.p.m., driving a single propeller shaft.

Despite all the painstaking work which had been devoted to this project, it was not an immediate success; the first tests of the *Turbinia* revealed a new problem, that of designing a propeller which would work effectively at a speed suited to that of the turbine. Existing types of screw propellers rarely ran at much more than one-tenth of the speed at which the turbine could be made to work efficiently. In tests with such propellers

at high speed, Parsons encountered an unexpected new phenomenon, known as "cavitation," in which the propeller cut a hole in the water, as it were, producing a vacuum and losing propulsive effect partially or completely.

More patient work followed, in which Parsons made many different models of propellers and tested them in a dynamic flow tank of his own invention, which enabled the propellers to be observed under actual working conditions and their thrust measured. By this means, he not only solved his own problems, at least to the stage of producing practical results, but also contributed a vast amount of knowledge on the design of propellers, water turbines, and hydrofoils, which is still found extremely useful at the present day. His test tank and models are still preserved in the Newcastle upon Tyne Museum. On the strength of the data thus obtained, it was possible to design the propelling machinery to work much more efficiently at high rotational speed.

The first public appearance of the *Turbinia* was as spectacular as that of a gladiator in the arena. It took place in 1897, on the occasion of the historic Navy review at Spithead, where the British Navy, the largest in the world at the time, was assembled to do honour to Queen Victoria on the 60th anniversary of her accession to the throne. Suddenly, between the lines of the majestic ships, a tiny intruder appeared, moving so swiftly that no other craft there could overtake her. It was the *Turbinia*, which in her improved form, now achieved a speed of 34½ knots, over 10 per cent. faster than any destroyer then in existence.

Though the Admiralty, and marine engineers all over the world, were duly impressed by the performance of the *Turbinia*, Parsons' struggles to establish the turbine as a practical engine for ship propulsion were by no means over. The economy of his early turbines was not all it should be, and was worse at lower or cruising speeds than at full power. This was a serious disadvantage in ships which had to carry fuel for long voyages. Owing to the momentum of the turbine, it was more difficult to manoeuvre than a reciprocating engine, which could be stopped and reversed almost instantly.

It is probable that the factor which swayed the balance in favour of the turbine for naval vessels was its size and shape in relation to power output. Existing engines, to produce the

power needed for a fast battleship, had to be so large and heavy that it was quite a problem to accommodate them in a hull already weighed down with guns and armour. They were also topheavy, and it was impossible to protect them against shellfire. The relatively small turbine, of convenient shape to install well below the water line, offered quite new possibilities in the design of naval ships. Not only were nearly all destroyers and cruisers soon to be equipped with turbines, but an entirely new class of heavy battleship, the *Dreadnoughts*, and also almost equally large, but light and fast battle cruisers, with turbines of powers up to 50,000 h.p. and more, were built in the early years of the 20th century.

Experience with these ships enabled the turbine to be further improved, and to be run at lower speeds without undue loss of efficiency. Just as the research in design of propeller blades had enabled them to run faster, similar experiments in turbine blades enabled them to make good use of steam at lower velocities. The early Parsons turbine had flat rotor and stator blades, at an angle of 45 degrees to the shaft axis, formed by machining from solid brass. It was soon found that these impeded free flow of steam, and blades of special shape were evolved, which offered much less resistance, and took advantage of the natural expansion of the steam in its devious passage through the multiple stages, from high pressure at the admission end to vacuum at the exhaust end.

In explaining the theory of the reaction turbine, it is sometimes stated that the steam " bounces " off the stator blades on to the rotor, back to the next row of stator blades and so on. This is a facile explanation, but it is not correct, as impact and rebound are fatal to efficiency. Only a smooth, ordered flow will enable the energy of the steam to be turned into useful work.

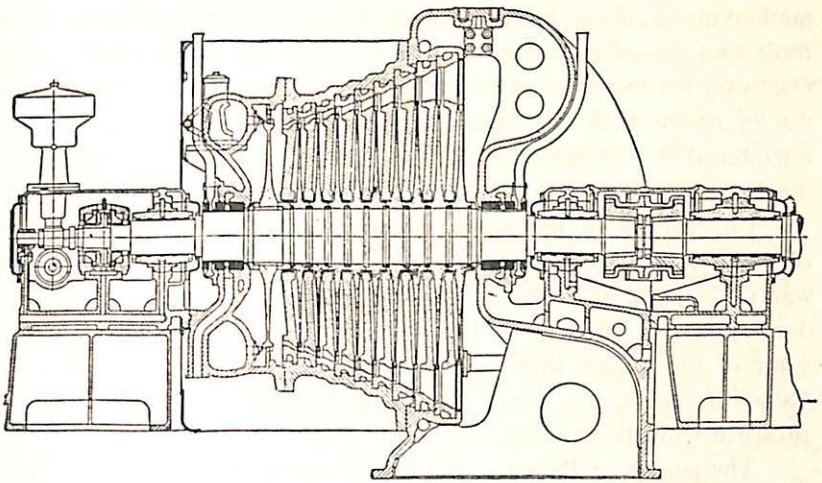
In order to prevent the leakage of steam around the shaft at the high-pressure end of the turbine, some form of seal or gland is necessary. The old-fashioned " stuffing-box " employed for the piston and valve rods of reciprocating engines was packed with soft packing, such as cotton impregnated with tallow, or asbestos-graphite. Later high-pressure engines used metallic packing, consisting of spring-loaded segments of anti-friction alloy. Neither type was suitable for use with turbines, as the

rubbing friction, even under most favourable conditions, was greater than could be tolerated, in view of their high speed and low torque.

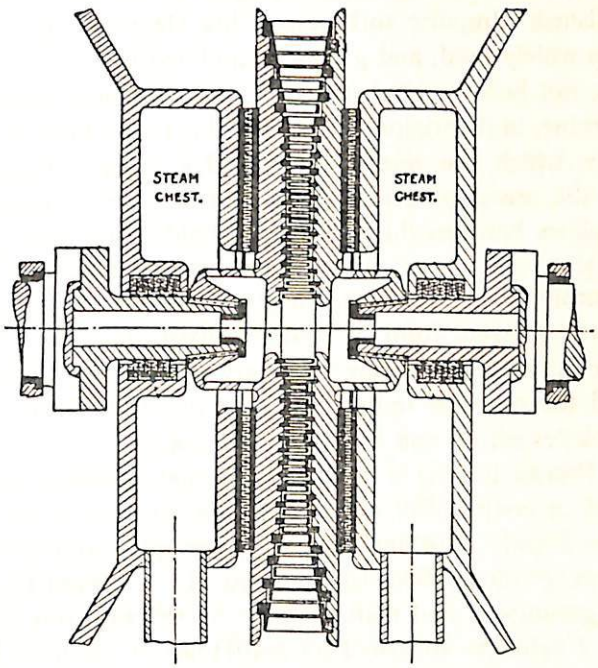
It was therefore necessary to find a more efficient substitute for the stuffing-box, and Parsons invented the steam-packed or "labyrinth" gland, in which alternate moving and stationary rings, having no physical contact with each other, reduce the steam pressure by gradual stages till it literally "gets lost" before it emerges at the outer end of the shaft. Parsons also introduced continuous lubrication by forcing oil under pressure to all main shaft bearings, and afterwards cooling, filtering and recirculating it in a closed circuit system.

The passage of steam from one end of a turbine to the other sets up a thrust which in large engines would be difficult to counteract by any available form of bearings. To balance this, the turbine can be made double-ended, steam being admitted at the centre and exhausted at the two ends. This is not always convenient, and another alternative is to employ a dummy rotor, without blades, of such a size that the steam pressing against it produces the counteracting thrust. In a ship, the thrust created by the screw propeller could be used to balance that of the turbine, but as this must be transmitted through a long shaft, it is not always desirable, and more often propeller thrust is taken on a special form of bearing as close to the stern as possible.

Early turbine-driven ships employed direct drive to the propeller, but the speed of the latter was still too high for really efficient working, and Parsons therefore set about the task of producing reduction gearing capable of transmitting far higher power than had ever been attempted before. In the same year as the *Turbinia* made her successful debut, a 22 ft. launch, *Charmian*, was fitted with a turbine running at 20,000 r.p.m., and geared at a reduction ratio of 14 to 1 to a single propeller by means of double helical reduction gears. This form of gearing, or "herring-bone" gearing as it is called, has since become the standard form for high power. It runs more smoothly than gears with straight axial teeth because there is no sudden transfer of load from one tooth to the next; it is gradual and progressive due to the spiral angle of the teeth, and by opposing right and left-hand spiral gears against each other, the end thrust is balanced. It demands the most



Early English Electric compound impulse turbine producing 10,000 kW. at 1,500 r.p.m.



Ljungstrom radial-flow contra-rotating turbine.

meticulous accuracy in production, however, and special machine tools had to be developed before it could be made in the sizes necessary for the turbines of large ships. The gearcutting is carried out in rooms held at constant temperature, so that no errors are introduced by expansion of the metal, and once started, the machines must not be stopped until the operation is completed.

Lubrication of the gears, when installed, is by high-pressure oil jets directed between their teeth. By the time of the first world war (1914), geared turbines were successfully employed in British destroyers and cruisers, with considerable gain in efficiency, while some of the largest ships had high-pressure cruising turbines with reduction gears, to assist the main turbines running at lower pressure with direct drive.

The genius of Parsons, and his diligent endeavours to develop the steam turbine over a period of more than 20 years, has achieved world recognition, if only by the fact that nearly all the successful turbines produced by other inventors, though differing widely in details of design, embody some of the principles which he established. Impulse turbines on the De Laval principle are much less widely used, and generally confined to lower power, but they have not been without influence on subsequent design. The Curtis turbine, in its original form, resembled a multi-stage impulse turbine in which the nozzles and blades became progressively larger as the pressure became lower and volume increased. Diaphragm plates between the rotor discs divided the casing up into compartments, and were pierced to form the nozzles. In the Stumpf turbine, later developed by Riedler, an impulse wheel was used with a different form of blade, to work in conjunction with nozzles set at a tangent to the periphery of the wheel. Ljungstrom developed the outward radial flow type of turbine, with annular rows of blades set on one or both sides of a disc.

The Rateau turbine is of the multi-stage impulse type, and is often used in conjunction with the Curtis form of blading at the low-pressure end. Turbines on this principle, with or without various modifications, have been extensively employed for driving electrical generators, and manufactured by several firms, including Fraser & Chalmers, British Thomson-Houston, English Electric, Brush Electrical Co., and Metropolitan-Vickers.

In some forms of turbines, the blades in the casing, which would normally form the stator, rotate in the opposite direction to the rotor. This does not double the power obtained, as sometimes fallaciously stated, but it halves the speed of the rotating parts in relation to the steam velocity. For some purposes, where contra-rotating shafts can be employed, this arrangement is useful, but in other cases it is awkward and inconvenient.

Apart from the difficulty of changing the speed of a turbine, already mentioned, it is impracticable to reverse its direction, and for the purpose of driving a ship, these disadvantages impair facility of manoeuvre. It is usual to provide separate turbines, suitable only for short runs, for going astern, and these can also be applied to act as brakes when it is necessary to stop promptly in emergency. For other duties than ship propulsion, such as generating electricity, unidirectional movement at constant speed is employed, and these complications do not arise.

Chapter IV

INTERNAL COMBUSTION TURBINES

ENGINEERS are never content to rest on their laurels; they are never satisfied with their own achievements, and always have the urge to press onwards to greater heights of power and efficiency. No sooner has one form of motive power attained predominance than a rival arises to challenge its supremacy. There is, however, often a wide gap between the conception of a principle and its practical fulfilment, not to mention an uphill struggle against new problems of design and construction. The steam engine reigned for over a century before it became possible to produce any other engine of comparable efficiency, namely, the internal combustion engine, which only became possible through the improvements in engineering methods and materials which took place towards the latter end of the 19th century.

The first and most obvious advantage of the internal combustion engine over the steam engine is that it eliminates the need for a boiler, which is often the largest component of a steam plant, and the most difficult to regulate and maintain in proper working order. For mobile applications, therefore, where lightness and compactness are essential, internal combustion engines soon found favour, and it is easy to understand why they have almost completely superseded the steam engine for transport on land and in the air; at sea, the comparative merits of the two engines are as yet still in the balance. By combustion of fuel inside the cylinder of an engine, it is theoretically possible to avoid much of the loss in heat transfer which occurs when it is burnt in a boiler, but this advantage is not always attained in practice. At present, thermal efficiencies of the two types of engines, at their best, do not approach theoretical ideals, but in some of the best examples they run about neck and neck.

The great majority of internal combustion engines are still of the reciprocating type, but with the increasing demand for engines of high power, the case for the adoption of " gas " turbines as they are usually called is becoming ever stronger. It is safe to say that the fast and powerful aircraft of to-day could not exist if they relied upon piston engines for their propulsion.

The first patent for a gas turbine was taken out in Britain by John Barber, in 1791, only a few years after James Watt's momentous improvements in the steam engine. Although the design of this engine was very crude, it is interesting to note that it contained all the essential elements of the modern gas turbine, namely, a compressor, a combustion chamber, a turbine wheel, and reduction gearing. In addition, it specified a gas producer, in which fuel was gasified by heat, and separate receivers for gas and air prior to their admission to, and ignition in, the combustion chamber.

Although little appears to have been done in the 19th century to develop a practical gas turbine, many engineers were beginning to devote serious attention to it in the early years of the present century. Several promising schemes were put forward, and formed the subject of patent specifications, though it is not known how many of them were followed up by practical research. The possibility of producing a gas turbine was clearly envisaged by Parsons in a patent granted in 1884, and seventeen years later he also patented an axial flow air compressor, of a type which has been developed in later years for use in gas turbines. Dr. S. A. Moss in America, and Stolze, Jendrassik and Karavodine in Europe, also contributed to early experiments in gas turbine design.

Two of the greatest obstacles to progress in the development of a practical gas turbine were the lack of metals capable of withstanding the extremely high temperatures involved, and difficulty in supplying an adequate volume of gas under pressure to the combustion chamber. In any form of heat engine, efficiency depends on the range of temperature which can be effectively utilised, and this is more than ever important in an internal combustion engine, where the lower working temperature range cannot be extended by condensing, as in a steam engine, and the gases have to be exhausted while still containing a good deal of heat energy. In a gas turbine, the blades are subjected to a continuous searing

flame, and the problem arises of finding a metal which will not only stand up indefinitely to working at nearly white heat, but will also retain mechanical strength to resist centrifugal force due to extremely high speed, at this temperature.

The reciprocating internal combustion engine is capable of dealing with the high temperature problem only because combustion is intermittent, and the combustion chamber is cooled by air in between cycles, also by external means such as a water jacket. The combustible mixture is supplied to the cylinder by using the piston as a pump during the admission period. Both these facilities are lacking in a turbine, which, moreover, must be supplied with a very large quantity of gas to keep up continuous combustion. While it may be possible to employ a reciprocating type of compressor for this purpose, it is clearly undesirable to do so, as it largely defeats the object of the turbine itself; the compressor might just as well be combined with the working cylinder, as it usually is in normal engine practice. The development of an efficient rotary compressor which could be driven from the turbine shaft was therefore a necessary step in producing a practical gas turbine.

Whereas many of the early gas turbines were designed to operate on what is termed the "constant pressure" cycle, the difficulties above mentioned led some experimenters to adopt the "constant volume" cycle. Neither of these terms is truly descriptive, because some changes in both pressure and volume take place in each case; but the essential difference between them is that in the former, communication between the combustion chamber is always open, but in the latter, the combustible mixture of gas and air is pumped into a closed combustion chamber, and is admitted to the turbine after ignition, through an automatic or mechanically operated valve. The former method is capable of producing maximum output from a turbine of given size, and constant pressure conditions in the turbine are favourable to efficiency, but both the temperature and the gas supply problems are difficult to cope with. On the other hand, these problems are rendered less acute by adopting the constant volume cycle, but the intermittent action reduces the turbine output, and thermal efficiency is lower. It is also undesirable to introduce valves, which obstruct free flow,

and are liable to give trouble when working at very high temperature.

In a turbine which must be entirely self-contained, the problems involved in both the compressor and the turbine itself cannot be dissociated, and this complicates development work. Unlike the steam turbine, in which pressure is supplied from an outside source, and the turbine can be studied as a separate entity, the two functions of a gas turbine system are interdependent, and practical success depends not only on their individual efficiency, but also their compatibility with each other. In some of the early gas turbines the power developed by the turbine was all used up in driving the air compressor.

Dr. S. A. Moss, mentioned earlier, calculated that the usefulness of a gas turbine might be restricted by reason of internal losses. If a turbine theoretically produces 100 h.p., and its compressor requires 49 h.p. to drive it (not counting losses in either case), there should be 51 h.p. available surplus for useful work. But in practice, both the turbine and the compressor may have no higher efficiency than 70 per cent. each. So that the turbine would develop only 70 h.p. while the compressor would require $\frac{100 \times 49}{70} = 70$ h.p., all the power thus being absorbed, leaving nothing for external duties.

One of the earliest successful gas turbines was designed by H. Holzwarth, of Mannheim, who managed to sidetrack the above problem, at least temporarily, by using separately-driven rotary compressors for gas and air. The Holzwarth turbines, several experimental versions of which were built in the period from 1905 to 1939, were of the constant-volume type, with multiple combustion chambers, fitted with automatic non-return valves for both inlet and discharge. After the chambers were charged with gas and air from the compressors, at a pressure of about 45 p.s.i., the charge was ignited, causing a rise of pressure of 3 to 4 times this figure, and delivered by way of the discharge valves and expansion nozzles to an impulse turbine. The ignition in the combustion chambers was timed so that they fired in a definite order, and thereby produced a fairly constant and even torque in the turbine despite their intermittent action.

The Holzwarth turbine was probably the first to be capable of continuous work over long periods, and in this respect may be claimed to have been a practical success, but it was not a self-contained power unit, and was never put into commercial production. One of these turbines, designed to produce 1,000 h.p., had a total output of only 160 h.p. and though, after rebuilding in improved form, the output was raised to 450 h.p., the thermal efficiency, calculated from available data, could not have been much more than 10 per cent. Nevertheless, the experience gained from experiments with these turbines was by no means wasted, as it contributed to the fund of knowledge on thermodynamics, which was exploited not only in later gas turbine design but, strangely enough, to steam boilers as well.

Mention of Rateau was made in the previous chapter in connection with the development of steam turbines. In more recent years, this name has been more closely associated with the development of turbines for working on exhaust gases of internal combustion engines for driving supercharger blowers. After many years of research work, in which many difficulties in dealing with high temperatures and speeds had to be overcome, these turbo-blowers have now become established as one of the most efficient means of boosting the output of aspirated engines.

The advantages of turbo-blowers are particularly applicable to aircraft engines operating at high altitudes, as the reduced atmospheric pressure enables the turbine to run more efficiently by reason of the increased pressure range of the escaping gas, and thereby drive the blower faster. A single stage impulse wheel is usually employed, admission to which is through a ring of stator blades, and it is designed to offer the least possible obstruction to the exhaust gases, so that it does not set up back pressure.

The modern development of the gas turbine may be said to date from the early 1930's, when a R.A.F. cadet, Frank Whittle, began a serious study of the problems involved in the jet propulsion of aircraft. Several other investigators had already come to the conclusion that the efficiency of aircraft could be improved by adopting reaction methods of propulsion instead of the airscrews then employed. In some of these experiments, normal aircraft engines were used in conjunction with ducted fans, sometimes

augmented by exhaust gas discharge or fuel burners in the air stream.

Whittle's approach to the problem was revolutionary, not only in using a gas turbine, but also in the manner of its application. While all the thermodynamic problems of turbine design still remained to be solved, mechanical efficiency, as such, was not the main aim. Instead of using the turbine to produce power for driving rotating machinery, its sole purpose was to generate large volumes of heated air, which, when discharged rearwards, produced the reactive force to propel the aircraft. The turbine was therefore only required to produce sufficient power to drive its own air compressor and fuel pumps, so that the conditions postulated by Dr. S. A. Moss would be no deterrent to its practical success. In other words, it was not necessary to ensure a substantial ratio of positive-to-negative work in the cycle.

The available metals for making turbine blades at that time were not satisfactory for working at the high temperatures which would be attained in a constant pressure combustion turbine, and this fact accounted for the general belief among engineers and scientists that this type of turbine could not be a practical success. However, many metallurgists were studying the possibilities of producing special steels for resisting high temperature, with its attendant scaling, corrosion, and hot-strength problems, and their efforts contributed very largely to the success of the early Whittle turbo-jet engines.

The particular conditions encountered in jet propulsion of aircraft were specially favourable to the employment of a gas turbine, firstly because a turbine was much better suited to produce power output at high altitude than a normal piston engine, in which aspiration, or "breathing" becomes difficult in the low atmospheric pressure encountered. Secondly, because in aircraft moving at high speed, the forward movement can be utilised to assist the intake of air, and thereby improve the efficiency of the compressor. Incidentally, it may be mentioned that given sufficient forward speed, air can be forced into the combustion chamber of a jet propulsion unit without the aid of the turbine-driven compressor; the pulse-jet engines of the V1 flying bombs, and ram-jet engines of later missiles which are launched from ramps or catapults at high speed, employ this principle.

In the first Whittle jet engines, compressors of the centrifugal type, basically similar to a fan blower or vacuum cleaner, were employed. These are fairly efficient for working at low pressures, and gave reasonably satisfactory results, but when the engines were designed to work at higher pressures their limitations became apparent. It is possible to step up the pressure obtained from a centrifugal compressor by making it with two or more stages, the delivery from the first stage being connected to the intake of the second stage, and so on. But generally speaking, higher pressures are attained more efficiently by using a compressor of the axial

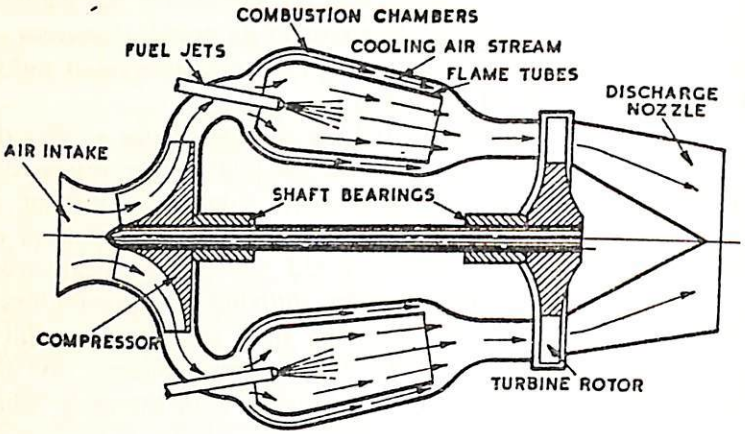


Diagram showing the principle of Whittle turbo-jet engine.

flow type, which follows the principles originally introduced by Parsons, and might be described as a multi-stage reaction turbine in reverse. Most powerful gas turbines now use this type of compressor, which may have anything from five to twenty rows of rotor and stator blades, depending on the delivery pressure for which they are designed. The blades are generally largest at the intake end, decreasing in size, and also in the diameter of the casing, towards the high-pressure end.

The air is discharged from the compressor into the combustion chambers, which are made with inner and outer compartments. A part of the air flows through the inner compartment or flame tube, into which fuel is injected by an atomising jet and ignited

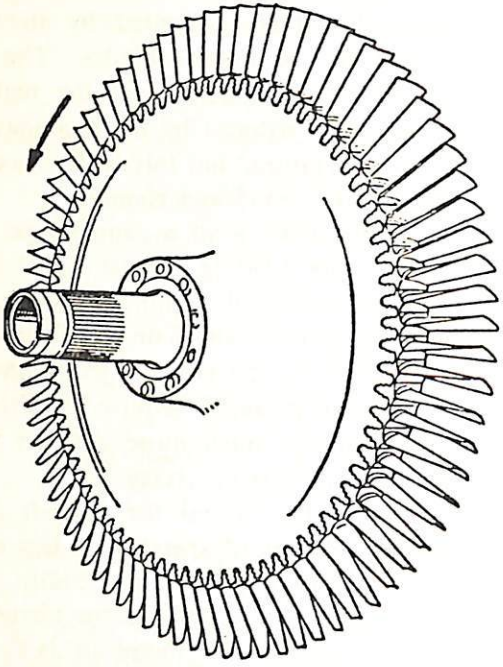
by means of an electric spark. The remainder of the air passes over the outside of the flame tube to prevent it from becoming overheated, and is then mixed with the combustion gases, reducing their temperature, but increasing the total volume of gas delivered to the turbine. No increase of pressure takes place in the combustion chambers, as this would cause the air to blow back through the compressor ; it is the increase of volume, produced by thermal expansion of the air, that supplies power to drive the turbine. For this reason, the higher the temperature attained, the greater will be the turbine efficiency, but this is limited by the temperature which can be tolerated by the turbine blades. The temperature attained in the combustion chambers is in the region of 1,800 degrees Centigrade, which is reduced by the secondary air stream to less than half this temperature, and this is the maximum which the blades will withstand for continuous running.

The turbine of a jet engine is of a simple type, with only a few stages of impulse-reaction blading in most cases. It is designed to make use of volume rather than high pressure, and is not required to generate the utmost mechanical efficiency from the available heat energy. For the purpose of jet propulsion, this is quite satisfactory, but when power is required to drive a rotating airscrew or other machine, a much more efficient turbine, with an increased number of stages, is necessary.

Jet propulsion is highly efficient for aircraft at very high speeds, but at the lower ranges of speed, it is less effective than airscrew propulsion, which is also more readily adjusted for variable speed by alteration of the pitch of the airscrew. Aircraft designed for moderate speeds are therefore better served by mechanical propulsion, using one or more airscrews.

Up to a certain limit of power output, piston engines are well suited to drive airscrews, and are still extensively used for this purpose ; but experience in the development of the turbo-jet engine enabled the efficiency of both the turbine and the compressor to be improved to such an extent that an engine capable of generating mechanical power on this principle became a practical possibility. The " prop-jet " and " turbo-prop " engines evolved as a natural conclusion, not only extended the usefulness of the gas turbine for aircraft, but enabled it to be applied to many other purposes.

In the prop-jet type of engine, both mechanical and reaction propulsion are available, so that efficiency at both low and high flying speeds is obtained, though in many early engines working on this principle, the mechanical drive was something of an afterthought, and no attempt was made to obtain the utmost performance from it. Two methods of increasing mechanical efficiency from the turbine are possible; first, by adding further stages of rotating and stationary blades to the compressor turbine, so that



Single-stage turbine rotor as used in jet engines.

it extracts more energy and reduces the ultimate exhaust pressure from the gas stream, and second, by adding another, independent turbine behind the primary compressor turbine, which serves the same purpose as before, but is free to rotate as a separate unit.

At first sight there is little difference between the two methods but in practice the free turbine has many advantages for producing mechanical power. By not being tied to the compressor turbine, it can be designed to produce the utmost torque over a wide range of speed, and is therefore more flexible in application. The

pressure and volume of gas which provides its working effort is dependent on the speed of the compressor, which can be kept high and constant, so that full power is instantly available at the free turbine when required. In this case the compressor turbine may be compared to the boiler of a steam turbine, the function of which is to maintain the supply of pressure to the actual motive power engine.

Following the success of the gas turbines in aircraft, they have now been employed to the propulsion of ships, and also to a smaller extent to stationary installations, locomotives and motor cars.

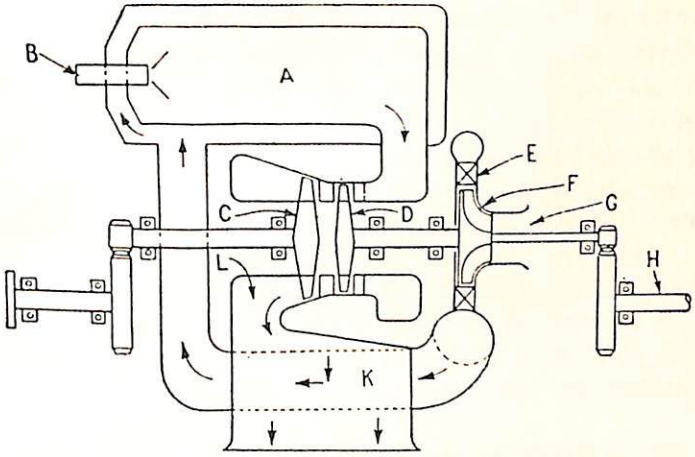


Diagram of turbo-compressor and free power turbine of early experimental Rover car. Key: A—combustion chamber, B—fuel atomiser, C—free turbine, D—compressor turbine, E—centrifugal compressor casing, F—impeller, G—compressor turbine shaft, H—auxiliary drive gearing, L—exhaust duct, K—heat exchanger.

Shortly after the war, the Admiralty began a series of experiments in the propulsion of small craft, such as motor gunboats, by gas turbines. These were at first adapted from aircraft practice, but the results obtained were so promising that special marine types of units were developed, some of them in much larger sizes, suitable for ocean-going ships. Up to the present, the headway in this particular application has been limited, as the economy of the gas turbine is as yet inferior to that of other forms of engine, and fuel capacity is a very important consideration in vessels which undertake long voyages; but as in the case of the steam turbine, this is not necessarily to be accepted as a permanent handicap.

Gas turbine locomotives have not yet emerged from the experimental stage, but Messrs. Brown, Boveri, in Switzerland (who, incidentally, built some of the Holzwarth gas turbines), also the Swindon works of British Railways Western Region, have produced locomotives which performed satisfactorily in main line service. Turbines for motor cars have been developed in this country by the Rover Car Company, and in America by the General Motors Corporation.

Chapter V

HYDRO-ELECTRIC GENERATING PLANTS

NOT many water turbines are employed nowadays to drive machinery directly by gearing or other mechanical transmission, as were the old water-mills. They are almost universally used to generate electricity, and the power stations in which they are installed are classified as hydro-electric plants. This application is in line with modern conditions, in which nearly all industrial power is transmitted by electricity, whether generated by water power or otherwise, but there is a particularly strong reason for it in this case. The availability of water power, as explained in Chapter II, depends on local conditions, and most of the places where a suitable fall and volume of water can be found are more or less remote from industrial centres.

A vast expansion in the production of electricity by water power has been taking place in recent years, and is still going on. The proportion of the world's power which is produced in this way is growing larger every day, though the power stations, located unobtrusively in unpopulated regions far from the busy haunts of men, are often unnoticed and unsuspected. Power stations and other industrial works are often accused of disfiguring the landscape, but many hydro-electric stations have a dignified beauty of their own, and may even be said to enhance the attractions of unspoilt nature by contrast, though this is admittedly a matter of personal opinion on which many people would disagree.

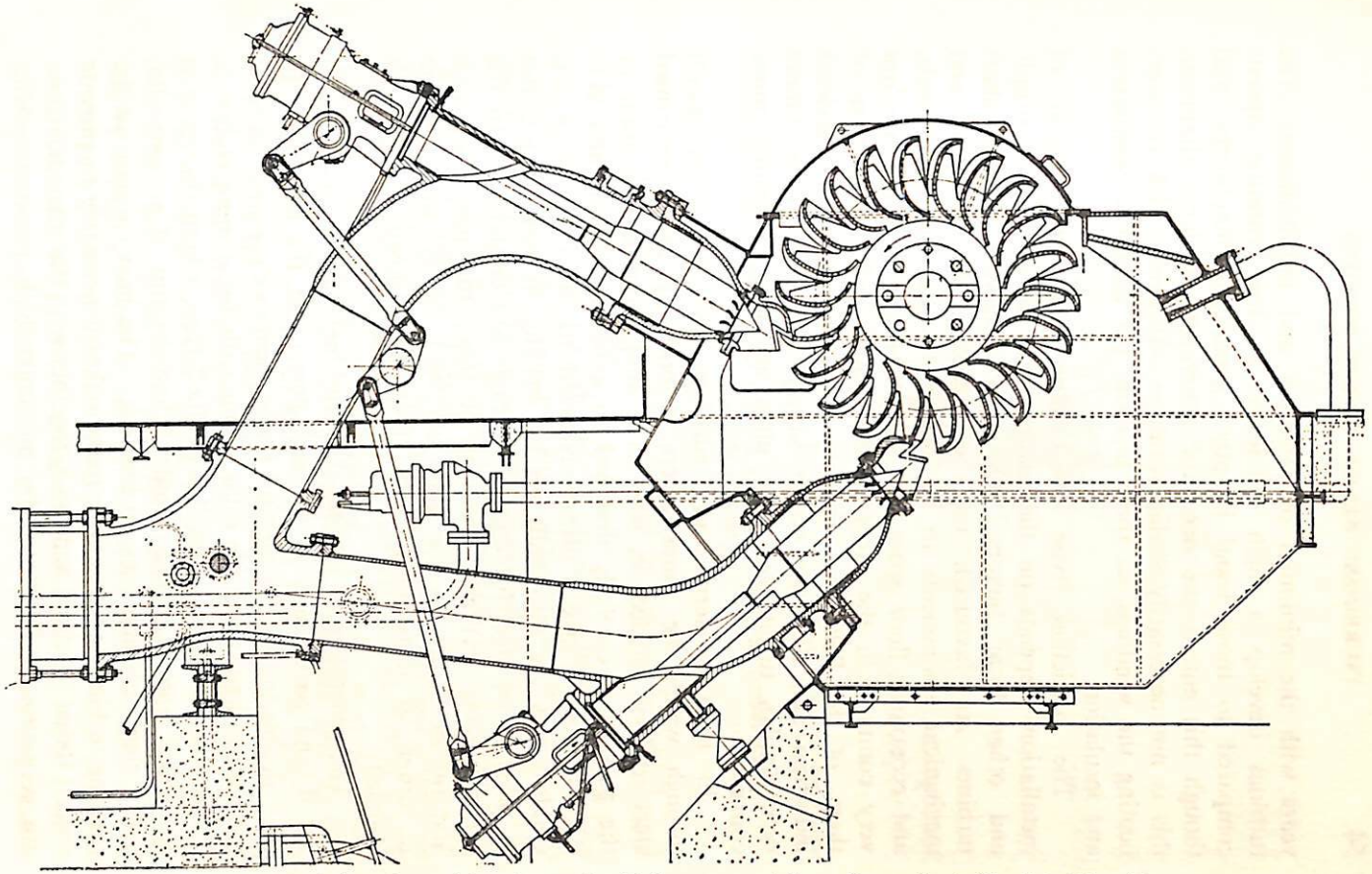
In the early development of water power on a substantial scale, which took place in the latter part of the 19th century, the sites for power stations were usually chosen where natural water courses, with ample falls or gradients, already existed.

Sometimes it was possible to adapt the flow of water by diverting it through a pipe or tunnel so that the minimum amount of building or excavation was required. For this reason, the Alpine regions of Switzerland, Germany, France and Italy were among the first which could be developed to produce electric power by water turbines. In the first-mentioned country, which has little or no production of fuel suitable for steam engines, almost all power, including that for one of the finest electrified railways in the world, is produced in this way.

Although latent possibilities for obtaining water power—namely adequate water supply from rainfall or other sources, and mountains or other elevations to produce a fall—are to be found in many other places, the task of harnessing them often presents much greater problems. In many cases a great deal of civil engineering is involved, including the building of huge dams to confine the water in the "catchment area" as it is called, and ensure that both the volume and pressure head are sufficient for driving the turbines at all times.

Often large valley areas have to be flooded and turned into artificial lakes, which submerge forests, houses and even complete villages. Naturally these drastic enterprises are not popular with the local inhabitants, and there has often been an outcry about the despoliation of natural beauty spots. It is, however, absolutely necessary, in the interests of the wider community, to conserve water in this way, not only for electric generating purposes, but also for the supply of the water itself to large cities or industrial districts. When it was first proposed to harness the power of Niagara Falls to generate electricity, the plan was opposed on the grounds that one of the most magnificent spectacles in the world would be spoiled; but now, after producing power for many years, it is still as great an attraction as ever, and certainly no less impressive.

Hydro-electric stations, when once built and put into operation, do not involve fuel costs, and are therefore one of the most economical means of producing power; but they involve colossal undertakings in the initial stages, and often take years to pay off the cost of all the damming, tunnelling, buildings and machinery involved. As a long-term policy, however, this is amply justified, because they will run for many



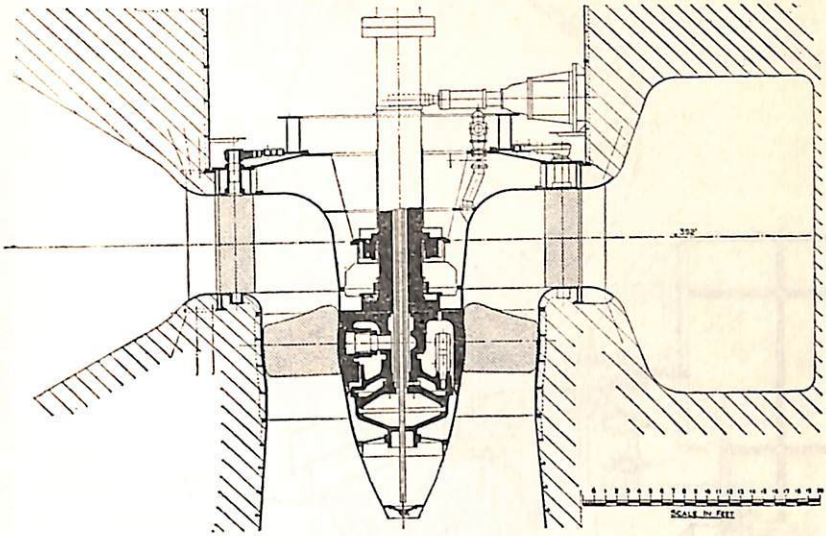
Horizontal impulse turbine for Tully Falls power station, Queensland (English Electric).

years with the minimum of attention and maintenance. The turbines develop a high efficiency at low running speeds compared to those usual in other generating machinery, and though this entails the need for generators of large diameter, this is not necessarily a disadvantage. It avoids risk of overheating the windings, as there is room for adequate ventilation and insulation.

The particular type of turbine, and its method of installation, depends on the arrangement of the water supply and other local factors. Generally speaking, vertical-shaft turbines are favoured, as they enable the electrical and mechanical components to be located on separate floor levels, and economise floor space. Horizontal-shaft machines are not very common in the larger sizes, though quite a number of them, of the Pelton or Francis type, are used for localised industrial and domestic power supply, and tubular or tunnel type Kaplan turbine-generator units are also becoming more common.

In most modern water turbines, the volute or scroll through which the water enters is built up from preformed steel sections, welded on site. The shape and cross-section of the passage is carefully designed to avoid restriction and skin friction, and to give a directional swirl to the inflowing water. Guide vanes are also built up by welding in some cases, but in other cases steel forgings or castings are employed. In the accompanying sectional drawings of these turbines, the vanes and runner blades do not stand out very clearly, and therefore in order to distinguish them, they are shown hatched or stippled.

The generators of vertical-shaft turbines vary a good deal in detail, and particularly in the arrangement of the bearings. In the " double-bracket " generator frame, bearings support the shaft both above and below the rotor. This calls for a more elaborate frame structure than in the " umbrella " type, where the rotor is suspended from a spoked " spider " like the ribs of an umbrella, and a single bearing goes up inside it. The heavy weight of the rotating turbine and generator parts makes it necessary to provide special thrust bearings, and these, together with the other bearings, are continuously lubricated by oil under high pressure. After

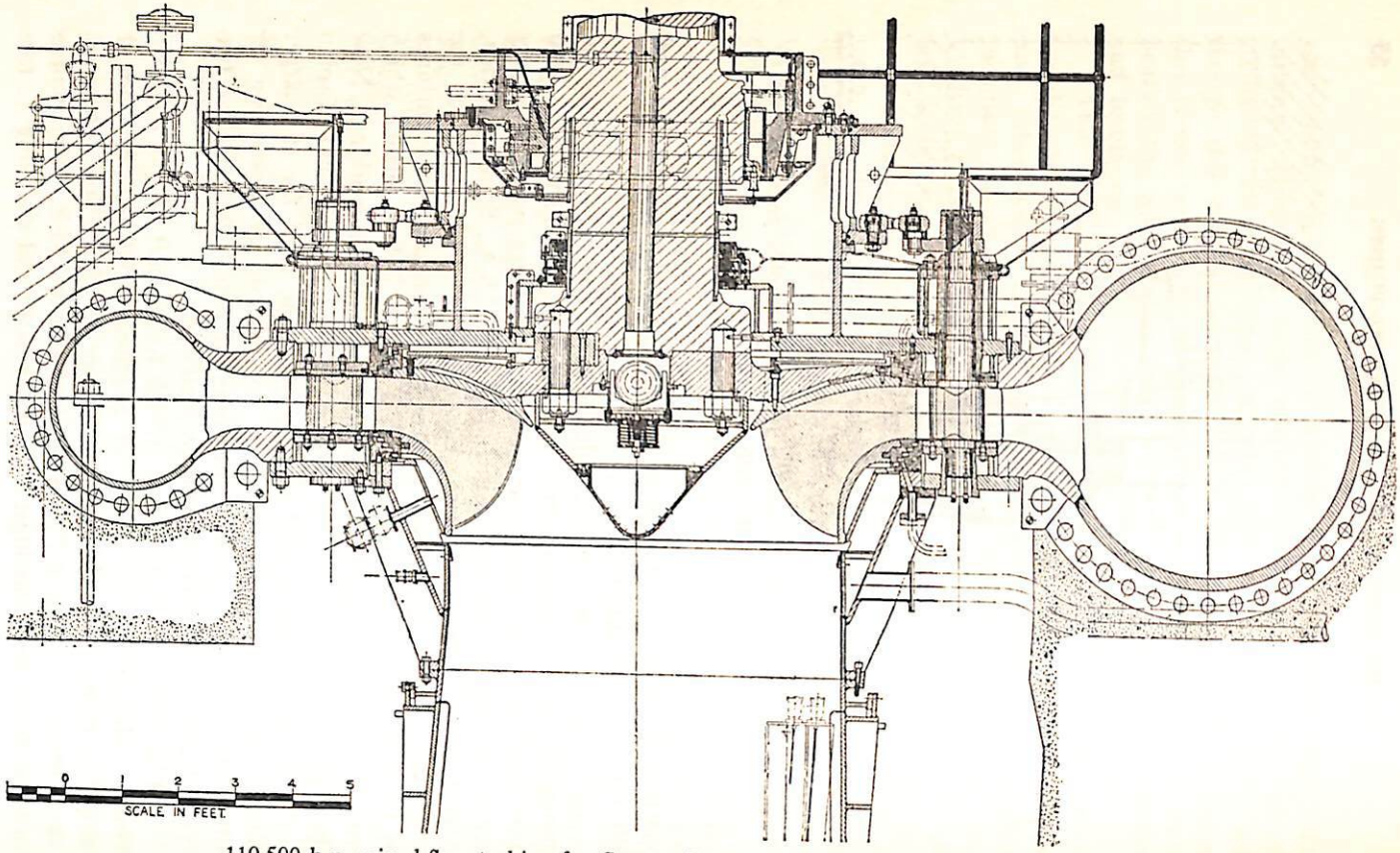


Cross-section of vertical turbine for Priest Rapids power station (English Electric).

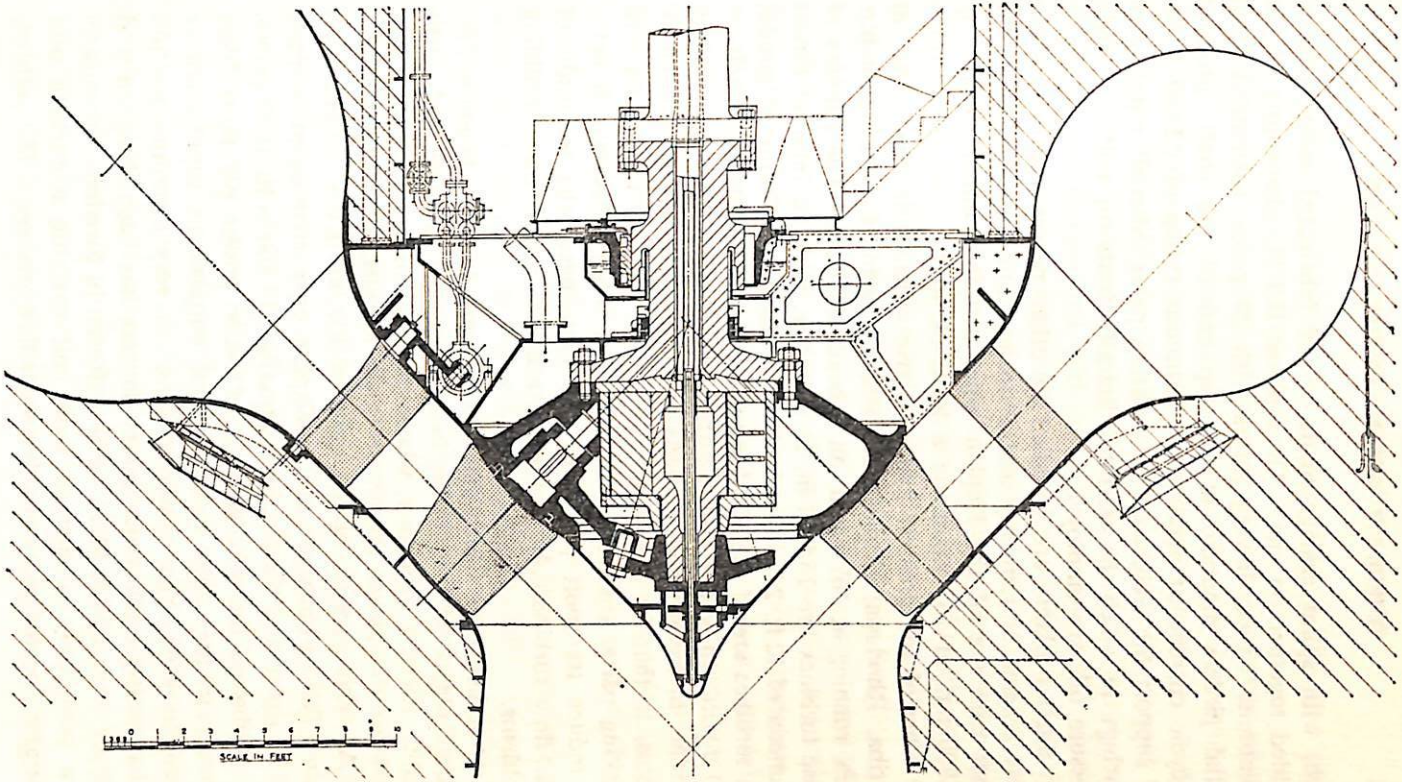
passing through the bearings the oil is collected, cooled and filtered, and recirculated.

In recent years, considerable progress has been made in the manufacture of hydro-electric machinery by British firms, who have built and installed generators of very large power in nearly every country in the world, including the U.S.A., South America, Africa and Russia. Messrs. Boving & Co. Ltd., one of the specialists in this class of work, have been producing water turbines in Britain since 1908, starting with a 90 h.p. Pelton turbine which was installed at Akaroa, New Zealand, and is still working. Now they produce some of the largest Pelton, Francis and Kaplan turbines in the world and have projects in hand for still larger output capacities. Space does not permit of describing or illustrating a large number of these in detail, but one or two typical examples may be briefly reviewed.

The Clunie power station, which forms part of the Tummel-Garry scheme of the North of Scotland Hydro-electric board, employs three vertical Francis turbines of 28,700 h.p., operating at a speed of 214 r.p.m. on a head of 145 to 165 ft. The runners are one-piece steel castings, 9 ft. in diameter and weighing 12 tons



110,500 h.p. mixed-flow turbine for Snowy T1 power station, Australia (English Electric).



Deriaz reversible pump-turbine for Niagara (English Electric).

each, with spiral casings made up of fabricated steel sections, welded together on site. Three-phase B.T.H. alternators of the "umbrella" type, having rotors with 28 poles, suspended from radial girders mounted at the top end of the shaft, produce 50-cycle current, at maximum continuous rating of 22,667 kVA. To support the weight of the rotating parts, Michell type thrust bearings, in which the assembly literally floats on a film of high-pressure oil, are employed.

Similar plants are installed in other power stations of the same scheme at Errochty and Pitlochry, but the turbines in the latter case are of the Kaplan type, two in number, producing 10,900 h.p. at 167 r.p.m. on a head of 46 ft.

One of the greatest hydro-electric schemes in the world, at Kariba, Rhodesia, employs six Francis turbines of 140,000 h.p. each, running at 167 r.p.m. on a head of 282 ft. The runners of these turbines are 15 ft. 1 in. in diameter, with an interval throat diameter of 12 ft. 2 in. At the Owen Falls Power Station, Uganda, the turbines are of the Kaplan type, rated at 21,000 h.p. each, at 150 r.p.m. on a head of 62 ft. One advantage of the Kaplan turbine, in cases where stations are located in places difficult of access, is that its overall size, and that of its components and working parts, are smaller than that of other types, which helps to reduce transport problems. In some cases the adoption of axial-flow turbines also simplifies excavation and other building problems.

Another firm which has manufactured many large hydro-electric plants for installation in various parts of the world is the English Electric Company, whose productions include the equipment for the power station at Priest Rapids, Washington State, U.S.A. This consists of ten units of 131,000 kVA (95,000 h.p.) each. The turbines are of the Kaplan type, running at a speed of 85.7 r.p.m. and the alternators produce 13,800 volts at 60 cycles.

Although the smaller sizes of water power plants are less spectacular, they fulfil a very useful purpose, as supplementary or auxiliary to larger power stations. A very ingenious method of harnessing small water power sources has been designed and built by Asea and K.M.W. at Skogsforsen in Sweden. It consists of a completely submerged bulb unit carrying a turbine and generator, located in an annular water flow passage. The turbine,

of the Kaplan type, has a rated output of 3,600 kW. at a speed of 250 r.p.m. on a head of 46 ft.

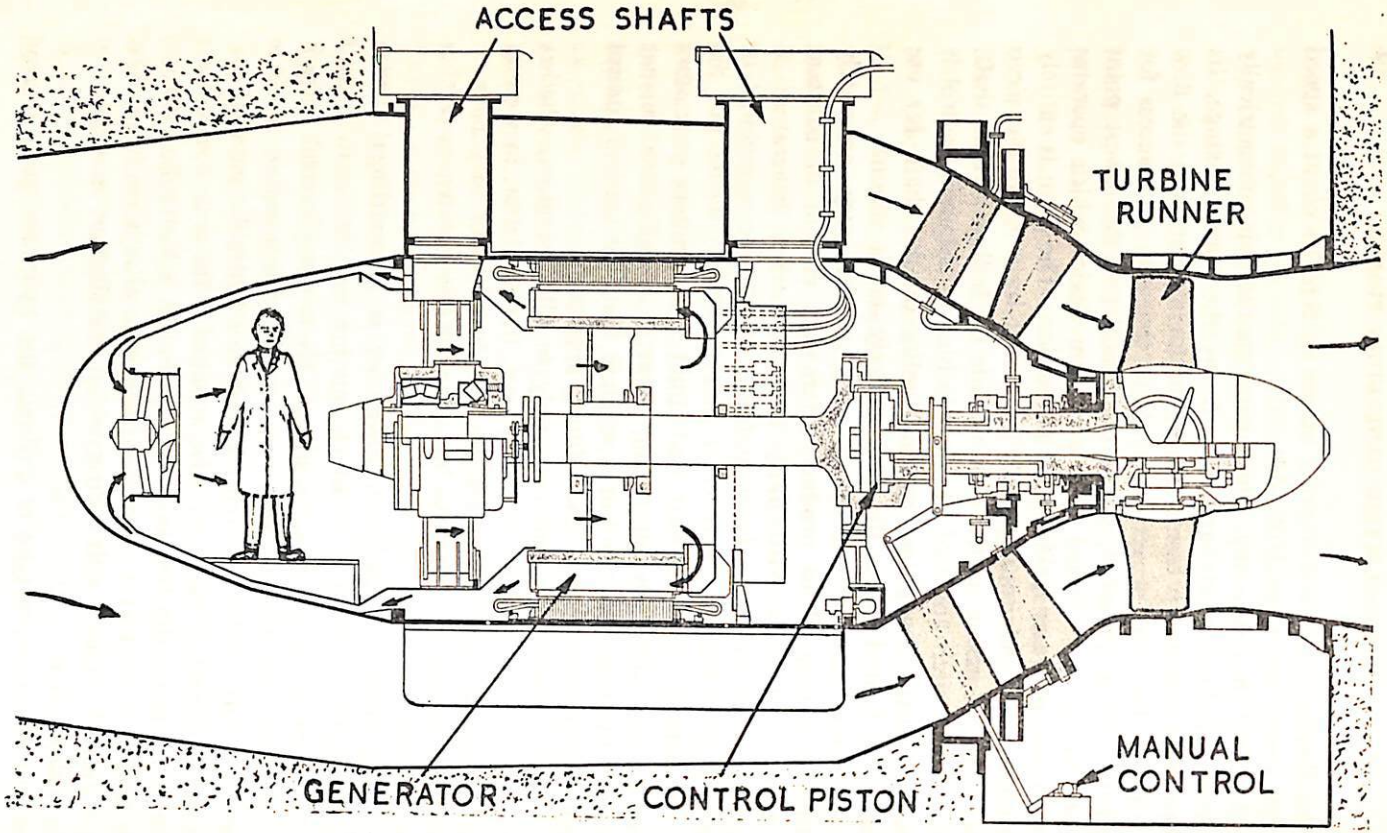
Located in a stay-ring, which supports the unit concentrically by radial hollow struts and also forms the water passage, its streamlined contour presents the minimum resistance to the flow of water. Two shafts, vertically above the unit, give access for inspection when required, and a drain outlet at the lowest point of the casing is provided with an alarm device which operates in the event of water leaking into its interior. The plant is entirely self-contained, and automatically regulated by a hydraulic servo system which, acting on the piston inside the hollow turbine shaft, controls the pitch angle of the turbine blades. Manual control is also provided, through an external collar on the shaft, for use when it is desired to put the plant entirely out of action.

Modern electric generators need to be very accurately controlled in speed to produce alternating current at constant frequency. This is particularly important when generators of varying types and sizes have to feed current into a regional or national grid system. Any error in synchronism would put the system completely out of gear, and might easily damage generators over a wide area, by subjecting them to out-of-phase current surges. Frequency regulation is so close that it is used to control synchronous clocks and other timing apparatus.

Speed governing problems apply to all generators, whether driven by steam, gas, or water turbines, but the latter, in view of their massive construction and the weight of water they have to deal with, need very powerful but none the less sensitive governing mechanism.

The basis of nearly all governors is a centrifugal device driven from the turbine, in which rotating weights act to control the movement of a rod or sleeve. This is not powerful enough to operate the turbine speed regulator by direct action, so it is used to control a form of relay known as a hydraulic servo-motor. A small, delicately balanced valve attached to the governor controls the pressure on the two sides of a piston in a hydraulic cylinder, so that it is kept in a state of equilibrium, always ready to exert a powerful force in either direction at the slightest movement of the relay valve.

In the Francis type of turbine, the hydraulic gear acts on



Submerged bulb-type hydro-generator unit at Skogsforsen, Sweden
(by courtesy of the Asea journal).

levers which control the guide vanes in the stationary ring through which water is directed into the turbine runner. The Kaplan turbine has the hydraulic cylinder located centrally inside the boss or shaft of the runner, acting on levers which control the pitch angle of the blades. Pelton wheels or other turbines in which one or more jets are employed, are often controlled by means of a conical plunger inside the jet, which is pushed forward to restrict the annular area of the orifice when it is necessary to reduce the power of the jet. It is essential that the control gear should act smoothly and without shock, also that restrictive throttling of the main water flow should be avoided, as this may cause cavitation.

In the Seewer system of regulation for Pelton wheels introduced by the English Electric Company, the controlling cone of the jet, known as the " needle head," is provided with retractable diffusing blades, which normally lie flush with the conical surface, but are projected from it very rapidly to diffuse the flow of water, when a reduction of speed is required, in advance of the main needle head movement.

The load requirements of electricity generating systems are by no means constant, or even predictable, during the 24 hours of the day. In some cases industrial power requirements are heaviest during the daylight hours, while domestic lighting calls for more power during the evening and is longer and heavier in the winter months. But rapid and unexpected load changes often take place, and the system must always be ready to cope with them at very short notice. This entails the necessity to keep generators on the line, even though there may be no immediate need for them, and the load on them may be very light.

Under these conditions, the plant is much less efficient than when running at full rated load, and considerable water is literally wasted. It is now common practice to use the unwanted current to pump water back to the main reservoir, thereby keeping the generators more usefully employed, and conserving the water supply, when outside power requirements are light. In the event of a sudden demand, it is only necessary to shut down the pumps and divert current to the outside circuit.

Most of the pump-storage systems which have hitherto been built have employed a three-unit machine in which the generator

is convertible to serve as a motor, and can be connected either to the turbine or the pump. In recent years, however, it has become possible to combine the functions of the turbine and the pump. Certain types of axial-flow or modified Kaplan turbines can be adapted to work as pumps by reversing the pitch angle of the blades, but their use is normally restricted to relatively low heads.

A new type of turbine, invented by Mr. Paul Deriaz, of the English Electric Company, is capable of dealing with the combined duties at heads up to 600 feet. It might be described as a cross between the Francis and Kaplan turbines, being of the mixed flow type, having stationary inflow control vanes, and also adjustable-pitch blades on the runner, with axes at about 45 degrees to the axis of its shaft. The power characteristics of this form of turbine are very good, giving higher mechanical efficiency than either Francis or Kaplan turbines at 20 to 50 per cent. load and equal to either at 50 to 90 per cent. load.

A particular feature of this turbine is that when the runner blades are in the zero or closed condition they form virtually a smooth cone, and therefore very little torque is required to start the runner when working as a pump, eliminating the need for elaborate electro-mechanical starting gear.

The first installation of Deriaz reversible pump turbines was in the Sir Adam Beck station of the Commission of Ontario scheme, where six units, each producing 45,000 h.p. at 92.3 r.p.m. on 45 to 90 ft. head, have been installed. As a pump, each turbine absorbs 55,000 h.p. at maximum discharge.

Chapter VI

STEAM POWER IN THE TWENTIETH CENTURY

FEW of the critics of modern civilisation, who are so fond of condemning the work of engineers and scientists, ever stop to realise that most of the material benefits and amenities which are taken for granted nowadays have only been made possible by the development of mechanical and electrical machinery. This has given us improved facilities in travel and communications, manufactured goods, and light at the flick of a switch, all of which were practically unknown little more than a century ago. At that time, nearly all industrial and domestic work had to be carried out by human or animal labour, and the only artificial lighting available was by candles, torches and oil lamps, except in some large towns, where coal gas had begun to come into use.

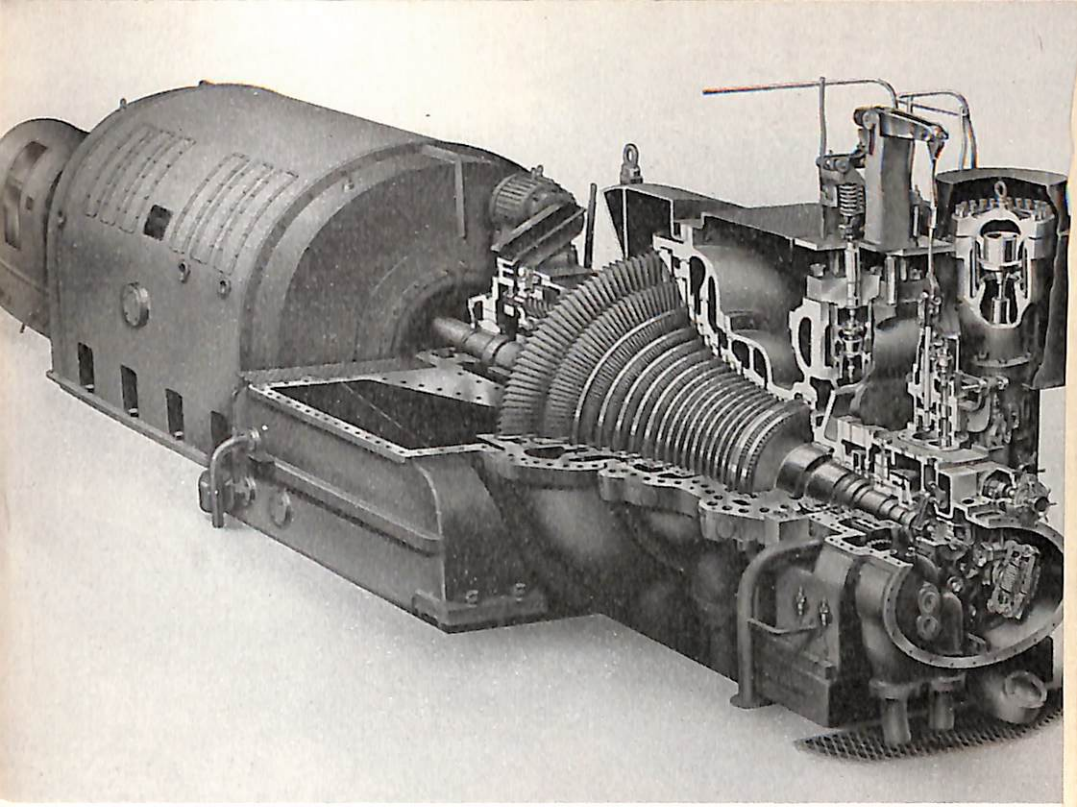
In the mechanisation which has taken place in all spheres within the present century, the steam turbine has played an increasingly important part. Without its aid, it would have been almost impossible to cope with the growing demands for power, and electric power in particular. Although nearly all large towns had their power stations as early as 1900, their output, compared to that of the present day, was very small ; most of them produced only a few kilowatts, but now there are many power stations rated at hundreds of megawatts, and output is still far below demands.

The steam engines employed in the old power stations were usually of the triple—or quadruple-expansion type of gargantuan size, with ponderous cranks and pistons. Though they gave the impression of irresistible power they were in fact unable to drive the generators at their most efficient speeds. They also called for skilled management and maintenance to keep them in proper working order.

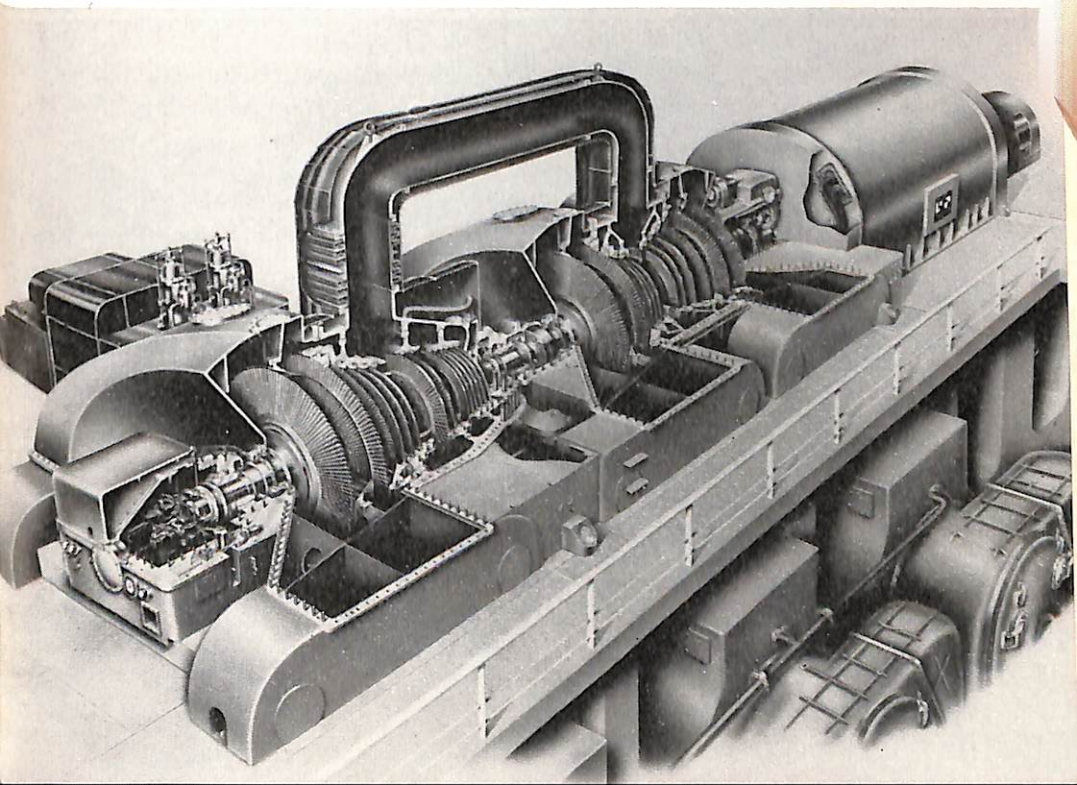
With the advent of the steam turbine, the entire aspect of electric power generation was changed. Not only was the size of the plant for a given horse power, considerably smaller, but the turbine produced speed enough, and to spare, for the most efficient generators which could be designed, so that these could also be made much smaller in relation to output. The modern power station is therefore much less spectacular, but immeasurably more efficient than it used to be. Whereas the reciprocating type of engine presents greater mechanical problems as its size and power are increased, the turbine knows no limits in respect of power development, and in many respects the problems in its design are inversely proportional to its size.

Turbines are largely dependent on their auxiliary machinery, including condensers, air pumps, and heat exchangers for their ultimate thermal efficiency. Small engines, and those having a large area of heated surface in relation to their power, are generally subject to considerable heat losses which lower their efficiency. Although the heated surfaces can be lagged with materials which do not readily conduct heat, the insulation which can be obtained in this way is far from perfect. It follows, therefore, that large turbines, which have relatively small areas of external surface exposed to the heat of the steam, conserve their heat energy better than any other type of engine. It is usually possible to avoid the need for pipes to transfer steam from high pressure to low pressure stages, but where these are employed, they are often combined with " reheaters " in which live steam is supplied to jackets or heat exchangers to make up heat losses in the system.

It has been mentioned that the efficiency of any type of heat engine depends on the range of temperature which can be effectively utilised. This, of course, is the basis of all steam engine theory, but nowhere can it be better exploited in practice than in the turbine. For this reason, most modern power stations use steam at the highest pressures which can be handled, with additional superheat to ensure that, despite inevitable heat losses in its passage through the turbine, its energy is available throughout the entire pressure range. At the other end of the scale, the condenser plays an important part by enabling most of the sub-atmospheric pressure (of approximately 14.7 lb per sq. in.) to be usefully employed, additional to boiler pressure.



(*Above*) Cutaway view of 25 mW compound reaction steam turbine (A.E.I.)
(*Below*) Cutaway view of 83 mW mixed pressure 2-cylinder steam turbine for Berkeley nuclear power station (A.E.I.).



(*Above*) Cutaway view of the Gach Saran power station. (*Below*) The Blackburn Palouste turbo-jet engine.

The condenser, (another form of heat exchanger) contains a large number of tubes through which cold water is circulated to cool the exhaust steam and reconvert it to water. In doing so, the volume of the steam is reduced to such an extent as to produce a more or less complete vacuum ; this is assisted by the action of the air pump, which extracts the condensed water, together with any air which it contains, or which leaks in through glands and bearings.

The reclaimed water, which having been distilled, is almost entirely free from impurities, is pumped to the feed tanks, and from thence, back to the boiler to be again converted to steam. Thus the system forms a " closed circuit," in which very little water is lost ; in fact, the amount of " make-up feed " required gives an indication of any leakages which might lower efficiency. In a well-maintained plant, a condenser vacuum of 29 inches of mercury, or even more, is usually considered necessary to efficiency.

Although the design of boilers is somewhat outside the scope of this book, a brief review of this subject will help to complete the picture of the power station equipment. The boilers originally employed in power stations were mostly of the Cornish or Lancashire types, consisting of horizontal steel drums with internal furnaces and flues. These were reasonably efficient for the steam requirements of the relatively low-powered engines of the period, but as power demands grew, they were found inadequate for producing either the quantity or pressure of steam required. Not only were they unsuited to pressures of more than 100 or 200 p.s.i., but their heating surface was insufficient to generate steam at high rates. If forced by increasing the intensity of the furnace, violent agitation of the water they contained, caused " priming " which carried water over into the steam line, or even to the engines, sometimes with disastrous results.

The first improvements in boilers consisted of fitting them with banks of tubes, which considerably increased the area of heating surface and thereby improved heat transmission from the fire to the water. Examples of early tubular boilers were the Scotch marine type and the Davey-Paxman Economic type, both of which employed return tubes from the back of the furnace flues to a smokebox at the front. These boilers are still extensively employed for moderate steaming rates, together with

others varying in details of design, but basically similar in principle. To make still further use of available heat, many boilers were fitted with feed water heaters, generally called " economisers," and superheaters to ensure proper drying of the steam after it had left the boiler, and make up for condensation losses in the engine.

The introduction of the water-tube boiler enabled steam to be generated not only at very high rates, but also at much higher pressures than were possible with internal-furnace or fire-tube boilers. Modern examples of these boilers consist almost entirely of tubes, except for such drums as are necessary for collection and distribution of water and steam, but these are relatively small, and therefore inherently stronger to resist pressure than the large drums of earlier boilers. The furnaces are under the boilers, and usually lined with firebricks or refractory materials, though " water walls " of closely spaced tubes often form the inner lining and serve as feed water heaters, or add their quota to the steam generating surface in some other way. In some high-pressure boilers, forced circulation of the water is necessary to avoid steam-locking in the tubes and to distribute the heat evenly throughout their entire area.

Superheaters are an essential adjunct to modern boilers, and these also consist of multiple tube banks, usually mounted above the main part of the boiler, but still in the path of the hot gases, and within the heat-insulated boiler casing. As pressures have increased, boilers have tended to become extended more in a vertical direction, and some of them are now as high as a four-storey house. Furnace space has been increased to ensure complete combustion of fuel at high rates. Coal is fed into the furnace automatically, in quantities proportional to the demand for steam under varying load conditions. Hand-firing of furnaces is now entirely obsolete. Mechanical stokers of the chain-grate or worm-feed type have been extensively employed, but are now being superseded by pulverised fuel systems, in which the coal is blown into the furnace by an air blast and burns practically instantly. Forced or induced draught is universal, as this enables the rate and completeness of combustion to be closely controlled. The high chimney stack, which was formerly necessary to ensure adequate natural draught, is no longer a landmark to locate the

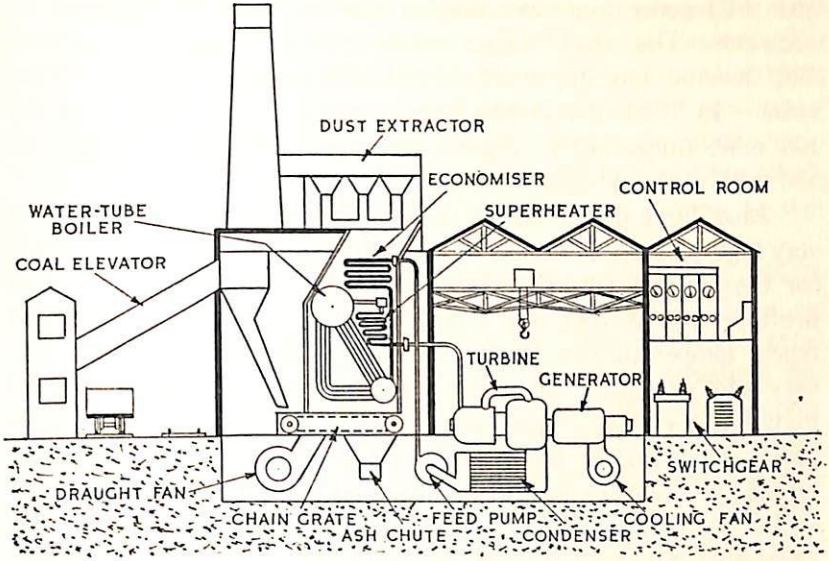


Diagram showing the arrangement of a modern steam power station.

power station, and heavy outpouring of smoke and soot is prevented by controlled combustion, aided by mechanical dust extraction plant.

In the usual arrangement of a power station, the boilers are erected on the ground floor, and occupy the major space in the building. Fuel, conveyed by rail, road or water, is elevated to bunkers on the top floor, and fed by way of hoppers and chutes to the furnaces. The turbines and generators are located on the first floor, with their auxiliary machinery, including condensers, oil and feed pumps, immediately below. Control gear is installed in an isolated room, often on an upper floor or in an annexe, with heavy-duty switch gear, transformers or other power equipment below or adjacent to it. The whole layout is a model of neatness and efficiency, giving little visible or audible evidence of the enormous mechanical and electrical power involved.

Some of the largest steam turbine generators in the world have been produced by a group of British companies which are now merged under the name of Associated Electrical Industries Limited. During the last 38 years, in which accurate records of power station thermal efficiencies have been kept, those equipped

with AEI generators have headed the list on no fewer than 32 occasions. The rate of expansion in the use of electricity is such that demand has approximately doubled in the course of ten years. In 1950, the largest sets produced in Britain were for 100 mW. (megawatts) output; ten years later, units of 300 to 550 mW. capacity were on order.

Most large power station turbines at the present day work on very high pressures, and are of the reheat type. A large unit made for the Central Electricity Generating Board employs a steam pressure of 3,500 p.s.i. at a temperature of 600°C. at the inlet and reheat temperature of 580°C. for the low-pressure stage. These very high pressures and temperatures call for the use of special materials for steam pipes, steam chests, nozzle boxes and other parts. Undoubtedly the experience gained in tackling the metallurgical problems in gas turbines has had its influence in improving steam turbines as well. The turbines direct-coupled to the generators run at 3,000 r.p.m. for 50-cycles output, or 3,600 r.p.m. for 60-cycles. Many of the largest turbines employ the Baumann multi-exhaust system, which avoids the need for excessively large casings and blades, by dividing the low-pressure steam up between a number of smaller compartments of the complete turbine.

As turbines are not mass-produced, nearly every individual plant has its own identity and differs in some degree from other plants. It is impossible to deal with all the many examples in detail, but the illustrations facing page 80 show characteristic types, with main features which are more or less common to all. The 60 mW. machine shown is described as a "two-cylinder" machine, the initial high-pressure expansion being carried out in the small turbine on the left, after which the steam is transferred, and at the same time reheated in its passage through the U-shaped pipe, to the low-pressure turbine. Here it enters in the centre and flows both ways, finally escaping by the two outlets at the bottom, to the condenser (not shown) located underneath. The casing at the extreme left contains the speed governor and control gear, while that at the right contains the coupling to the generator and also a motor and gearing, comparable to a motor car self-starter, the object of which is to enable the shaft to be turned when not under steam, for maintenance and inspection of the working parts.

Nuclear power is now being extensively employed in some of the world's largest power stations. Although nuclear energy is primarily an electrical phenomenon, the only way in which it can be harnessed for the production of power, up to the present, is by using its heating effect to produce steam or other high-temperature fluid energy. This in turn is fed to a turbine which does not differ in essentials from a normal steam turbine, though it may be modified in detail.

The heat is generated in an atomic pile or "reactor," which takes the place of the boiler in a normal steam plant. It can be applied directly to the water, but if so, the steam generated becomes radioactive, and this would necessitate screening the entire plant by surrounding it with thick walls of metal or concrete. Indirect heat transfer, through the medium of a liquid having a higher boiling-point than water, or even a fusible metal, enables this disadvantage to be avoided, but it is still necessary to screen the reactor. For this reason, the application of nuclear power is limited to plants in which the weight and the bulk of the screening do not present difficulties or disadvantages.

The most convenient form of nuclear power plant is that employed for generating electricity on a large scale. A considerable amount of pioneer work in this field has been carried out in Britain, including the highly successful experimental plant at Calder Hall. Ship propulsion by nuclear power, using turbines either to drive propellers directly or through electric transmission, has proved equally practicable, but proposals to build nuclear powered aircraft, locomotives or other vehicles have not yet materialised, for the reasons described above. It should, however, be realised that this form of power is yet in its infancy, and that great developments lie not far ahead. The subject of nuclear power generally is outside the scope of this book, and is only mentioned in passing to point out its intimate association with the steam turbine.

In the orthodox types of marine plant, with coal- or oil-burning boilers, the turbine has not entirely superseded the reciprocating engine. The latter is still extensively used for propelling moderate-sized cargo ships and other craft in which engine performance is not unduly taxed. But naval craft, such as destroyers, cruisers and aircraft carriers, employ turbines

of very high power, driving the propellers either through reduction gearing as already described, or through electric transmission. Both systems have their own particular advantages and limitations, gearing being generally more compact and direct, though it calls for the concentration of all the power equipment in a large engine room, where it may be very vulnerable to enemy attack.

Using the turbines to drive electrical generators, and then applying the current to motors driving the propellers, may appear unnecessarily complicated, but it enables the power plant to be divided into a number of smaller units, all individually protected, in separate compartments, and located in the most convenient positions, to distribute weight and stress on the ship's structure. In addition, the control of the ship can be carried out much more simply by electric switchgear operated from the bridge, instead of the older method in which the engines are controlled by the engine room staff, in response to signals transmitted through a telegraph system.

Though the Mercantile Marine were slower in adopting the turbine than the Navy, most of the first class liners of the twentieth century have been turbine-driven. Among early examples of these, mention may be made of the famous *Mauretania*, which had a long and distinguished record of service on the Atlantic route. The ship was built only 13 years after the *Turbinia* made her sensational demonstration, and the rapid growth of the turbine both in design and stature is shown in the comparative size of the two ships.

Some large merchant vessels have been made with main engines of the reciprocating type, with supplementary low pressure turbines either direct-coupled or geared to their shafts. The exhaust steam from the main engines is capable of making quite a substantial contribution to power, by further expansion in the turbines practically down to condenser vacuum, which would not otherwise be possible.

Many marine and land installations employ turbines for auxiliary duties, such as driving pumps for the various necessary services. The electric generators and ventilating fans in ships are often turbine-driven, and such duties give scope for relatively small and simple turbines of the impulse or impulse-reaction

type. Messrs. Greenwood & Batley, Ltd., of Leeds, have specialised in turbines of the De Laval type for many years, in sizes from three to 300 h.p. These occupy much less space than reciprocating engines of equivalent power, with weight in proportion, and their requirements in respect of attendance, lubrication and maintenance are much lower.

The basic design of these turbines follows the principles of the original De Laval impulse turbine, having a single wheel with crescent-shaped blades and one or more divergent nozzles located around the inner steam chest casing, or fitted to a nozzle ring. Steam enters the annular steam chest by way of a main stop valve and a sensitive centrifugal speed governor valve of the balanced double-beat type. In some cases control valves are fitted to individual nozzles. In addition to the sensitive governor, which is driven through worm gearing and a vertical shaft, the lower end of which also drives the lubricating pump, an emergency overspeed trip governor is fitted, which cuts off the steam supply entirely if the turbine should ever reach a dangerous speed by failure of the normal control gear.

The turbine wheel is machined from a forging of nickel-chrome steel and fitted with stainless steel blades, which are specially shaped at the root so that they can be anchored in milled seatings in the wheel. A flexible shaft, as described in Chapter III, is employed, running in forced-lubricated bearings, that at the tail (non-driving) end of the shaft being of the self-aligning type, so that it can accommodate itself to any distortion caused by heating or mechanical stress of the wheel casing.

In cases where the turbine is mounted as a complete unit with its own reduction gear, the pinions are formed on the shaft, but where the gearing or other form of transmission is separately mounted, a flexible coupling is fitted to take care of any possible errors of alignment. Owing to the high speed of the impulse turbine, most applications call for the use of a reduction gearbox with one or two stages of double helical gears.

Messrs. Greenwood & Batley also manufacture turbines of the multi-stage type for powers from 100 to 1,400 h.p. suitable

for electrical generators of 75 to 1,000 kW., and for working on steam pressures up to 650 p.s.i. at 500°C. The larger sizes of these are usually equipped with their own condensers, which are located within the main structure, immediately below the turbine casing.

Turbines of these and similar types are often arranged to make use of exhaust steam from auxiliary reciprocating engines in ships, or steam which has already been used for heating, distilling or other essential processing in industrial plants. Such turbines are generally referred to as "back pressure" turbines, as they often use steam which has necessarily been rejected at a few pounds pressure, but many of them are capable of doing useful work when fed with sub-atmospheric steam, so long as there is some difference of pressure between this and the condenser vacuum. This is the nearest possible approach to "something for nothing" that can ever be attained in engineering, as the steam they use would otherwise have been wasted.

Chapter VII

GAS TURBINES FOR AIR, LAND AND MARINE USE

THE first important application of the gas turbine, as explained in Chapter IV, was for the propulsion of aircraft, and its development in this field is still progressing at a rapid rate. More efficient and reliable engines, both for jet reaction and shaft power, are constantly being produced to satisfy the requirements of larger and faster aircraft. The turbo-jet engine, for high-speed and high-altitude flying, might be described as the most powerful engine on earth, if rockets for space exploration are excluded. Single turbo-jet units capable of producing output equivalent to 40,000 effective horse-power at a speed of 450 m.p.h. are common to-day, and further increases of power are possible. As a prime mover, however, the thermal efficiency of this type of engine is lower than is desirable—rarely more than 15 to 18 per cent. — and its heavy consumption of fuel is only justified under the special conditions for which it was originally designed.

At lower speeds and altitudes, the turbo-prop engine, though heavier, more complicated, and generally of lower actual power output, is more economical and capable of a wider range of application. The specific fuel consumption of this type of engine is in the region of 0.5 lb. per hour per lb. tractive effort, while that of the turbo-jet engine is often nearly 0.9 lb. per hour for the same tractive effort.

British aircraft manufacturers have pioneered the development of both types of engines, and are still in the forefront of their design and production. A large proportion of the world's aircraft is propelled by turbines built in Britain by Rolls-Royce, De Havilland, Armstrong-Siddeley, or Bristol Aircraft (the last two are now merged as Bristol-Siddeley Engines Ltd.) and many

foreign firms manufacture British-designed engines under licence.

Nearly all aircraft of large size built at the present day employ gas turbines for propulsion. Apart from their obvious advantages of high performance and power-weight ratio, they require little maintenance and will run for long periods between overhauls; they are not choosy about fuels, which may be of lower grade and higher flash point than those necessary for piston engines. Mechanical breakdowns of aircraft turbines are rare, though failure of the turbine or compressor blades is liable to be very serious if it does occur for any reason. It is therefore necessary to take the most stringent precautions in the design, construction and maintenance of all working parts to eliminate risk of such an occurrence. Nothing can be left to chance in a turbine, and it does not lend itself to shoddy production or cheeseparing in cost of materials or workmanship.

Besides being used for the propulsion of more or less orthodox types of aircraft, turbines have also made possible the development of revolutionary types with vertical take-off and other remarkable features. The jet engine is predominant in these types, but shaft-drive turbines are now increasingly adapted to use in helicopters, also in the Hovercraft, which, although still in the experimental stage, has given such promising results that it may soon be accepted as a standard amphibian form of transport. The large volume of low-pressure air required to produce levitation in this craft can most readily be produced by an adapted form of turbo-jet engine.

In some types of helicopters, the lifting airscrew, instead of being mechanically driven, is equipped with reaction jets in the tips of the blades; these are supplied with air from a turbo-jet through the hollow airscrew shaft and blades. The advantage of this method is that it eliminates the torque reaction which, in other types, tends to rotate the aircraft in the opposite direction to the lifting screw.

An interesting and versatile range of gas turbines for aircraft and auxiliary purposes is manufactured by Blackburn Engines Ltd. These include the Palas turbo-jet, the Palouste and Cumulus turbo-compressors, the Artouste compressor-cum-shaft drive, and the Turmo and Nimbus free-turbine shaft-drive engines. The Palas is a small and compact unit which can be accommodated in an

aerofoil " pod " for use as a main propelling engine for a light, fast aeroplane, or as a supplementary booster for a larger plane, to assist take-off and climb.

Both the Palouste and Cumulus turbines can be used to supply heated air at a pressure of 2 to 2.4 p.s.i., which can be applied to starting large turbo-jet or turbo-prop engines by blowing them round at high speed, while at the same time warming them thoroughly, ready for a quick take-off. They are available in the form of mobile ground units as part of aerodrome equipment. In industry, heated air can be applied very usefully in large-scale drying and heating processes.

The Artouste turbine, in addition to making use of the efflux of air, can also provide up to 100 h.p. at the shaft, but it lacks the flexibility of the Turmo and Nimbus free-turbine engines, designed exclusively for the latter purpose, and producing up to 400 and 900 h.p. respectively. These engines are applicable to many purposes which call for a light and compact source of power, readily portable and rapidly brought into operation. The Turmo can be installed in a completely self-contained 200 kW. generating set 12 ft. 1 in. long, 70 in. high, and 39½ in. wide, weighing 5,000 lb. all-on, and adapted for transportation by a two-ton truck, agricultural tractor or helicopter.

Up to a few years ago, the idea of a gas turbine for permanent land installation, capable of competing on anything like equal terms with the most advanced steam turbines, would have been almost unthinkable. Yet to-day there are many gas turbines in use, and many more under construction, for power station work with outputs up to 20 mW. A considerable amount of research work in this aspect of gas turbine development has been carried out by British firms, including Associated Engineering Industries, who have already produced gas turbine driven generators up to 7 mW., and have projects for sets up to 30 mW.

These generators incorporate turbines of the single-cycle single-shaft type, with the compressor and power units rigidly connected. This arrangement is suitable for the purpose of driving electrical generators, where torque requirements are relatively stable, and do not call for flexibility in speed control. They burn either gaseous or distillate fuels, which although more expensive than most boiler fuels for steam turbine stations, are often more

suited to local conditions. Where natural gas is available, or in the vicinity of oilfields, the gas turbine may be much more convenient, if not actually more economical, than the steam turbine. It is much more compact, the complete plant occupying little more than one-third of the space required for a steam power station. This may make a great deal of difference to the initial cost of the installation, and also its subsequent upkeep cost, all of which must be taken into account in the complete economical scheme.

The Anglo-Iranian Oil Exploration and Producing Company's power station employs three A.E.I. gas turbine generators, type L51C, each producing up to 7 mW. This plant supplies the whole power requirements of the extensive Gach Saran oilfield. The cutaway view (facing page 80) of a model of this installation gives a good idea of the arrangement of the turbines, generators and control gear.

There is no doubt that the development of the gas turbine for industrial purposes has been greatly influenced, and accelerated, by the knowledge and experience obtained from aero turbine practice. This is particularly evident in the case of the Proteus and Olympus turbines produced by Bristol-Siddeley Engines Ltd., which are direct adaptations of engines which already have had a distinguished career in aircraft. The Proteus is used in the Britannia air liner and has operated in service for over a million hours. Similar working experience is available in the case of the Olympus, which is used in the Vulcan bomber ; but being a jet engine, an additional turbine must be provided to convert its exhaust energy into shaft power.

Both these turbines have been satisfactorily adapted for use in driving electrical generators, and while their economy in terms of fuel cost per wattage output is inferior to that of steam plants, they have proved extremely useful as a supplement to steam power stations for dealing with peak load requirements. It has been explained in previous chapters that load demands vary widely, and generating capacity for maximum load must instantly be available, yet it is very uneconomical to keep generators running idly or on light load continuously.

The initial cost of a gas turbine is considerably lower than that of a steam turbine plant, and it can be brought into operation in a much shorter space of time. Moreover, it is much easier to

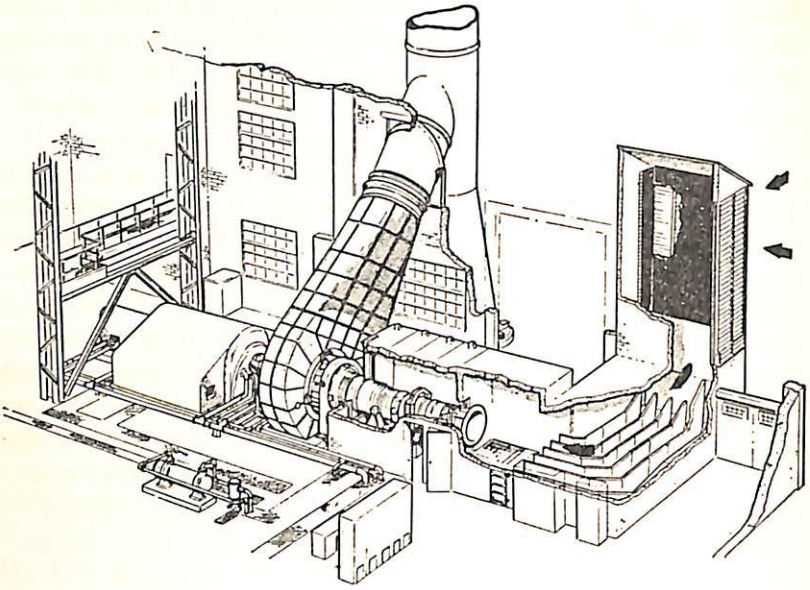
house, and can even be made portable if required, so that it can be located where loads are likely to be heaviest, and thereby reduce transmission line costs. In the overall capital and operating costs of electric power generation, it has been proved that the gas turbine, employed in this way, can make a substantial saving.

The Proteus-powered generator was originally produced in 1958, when the Bristol-Siddeley Company was developing the turbine mainly for marine application. At that time some problems in the supply of power to the works were encountered, and it was decided to employ the power produced by the engine on the test bed to useful purpose in an electrical generator. This experiment proved so successful that it was decided to put the engine on the market for industrial use. In many ways this was a breakaway from conventional practice, as nearly all industrial engines of any kind hitherto constructed were heavy and massive, and the idea of an engine weighing only $1\frac{1}{2}$ tons to generate 3 mW. was quite unprecedented.

The engine has a high-pressure compressor with one centrifugal intake stage and twelve axial stages, supplying air to eight combustion chambers. Fuel is injected into these chambers and ignited electrically, the resultant expanded gas first driving a two-stage turbine which is coupled to the compressor by a hollow shaft, through which the shaft of the separate free turbine, also having two stages, passes. Reduction gearing is employed to drive the generator at either 1,000 or 1,500 r.p.m. (according to the number of generator poles) for producing current at 50 cycles. Alternative output speeds, for 60 cycles, are 1,200 or 1,800 r.p.m. The fuel employed is kerosene or normal diesel fuel, but the system can be adapted to use natural gas where available.

Up to the end of 1961, four Proteus-powered stations, besides the experimental plant at Bristol, were built at Porlock, Lynton, Princetown and St. Austell, each producing 3 mW., to deal with peak load problems in the south-west of England. The normal power rating of the engine in each case is 4,250 h.p., at a fuel consumption of 0.58 lb. per h.p., and free turbine speed is 11,600 r.p.m.

These sets are completely automatic, and the power stations are unmanned, requiring attention only at specified periods for replenishment of fuel and lubricant supplies and other necessary



Arrangement of automatic power station, employing Bristol-Siddeley Proteus turbine.

services. They can be brought into operation by code signals over an ordinary telephone line, and are normally available for switching into the grid system in two minutes. In the event of any starting difficulty, which rarely arises, or other mechanical or electrical failure, the plant cuts out and signals are telephoned back to the main control station to indicate the reason for the shut-down.

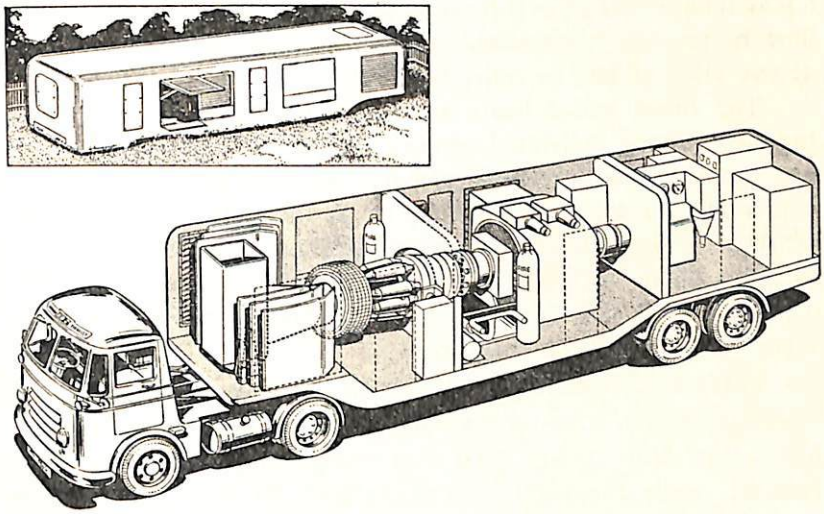
The 3-mW. set has also been adapted as a mobile power station by reducing the size of the plant, which involves little more than using a smaller, higher speed generator, having 4 poles, with a suitable change in the reduction gear ratio. In the transportable form, the weight of the complete "package" is about 19 tons, with an overall length of 34 ft., and a width of 9 ft. This includes all control and auxiliary gear required by the engine, but the switchgear for the generator is carried in a separate pack.

The Olympus engine, in its adapted form for industrial use, is fitted with a 2-stage free turbine running at 3,000 to 3,600 r.p.m., for direct coupling to a 2-pole alternator producing 50 or 60 cycles

respectively. By the elimination of reduction gearing, the construction and lining-up of the set is simplified, and there is some gain in mechanical efficiency. This plant has a rating of 15 mW., probably capable of increase up to 20 mW.

The marine gas turbine has made possible the development of light gunboats and other craft having a higher performance than could ever be attained with other types of engines. There is reason to believe that it could be applied to larger vessels such as destroyers and cruisers, with considerable saving in weight and space, besides increase of speed. In the early ships of this type, the hull had to be literally packed with machinery, the weight of which largely frustrated attempts to attain increased performance. Even when using steam turbines, the bulk and weight of the boilers and engine-room equipment often proved to be the limiting factor in improving power and speed. The high power-weight ratio of the gas turbine simplifies many problems in the design of ships, and its application to marine propulsion is progressing rapidly.

In the experimental work on the propulsion of small craft undertaken by the British Navy shortly after the last war, the first turbines used were by Metropolitan-Vickers, adapted from jet



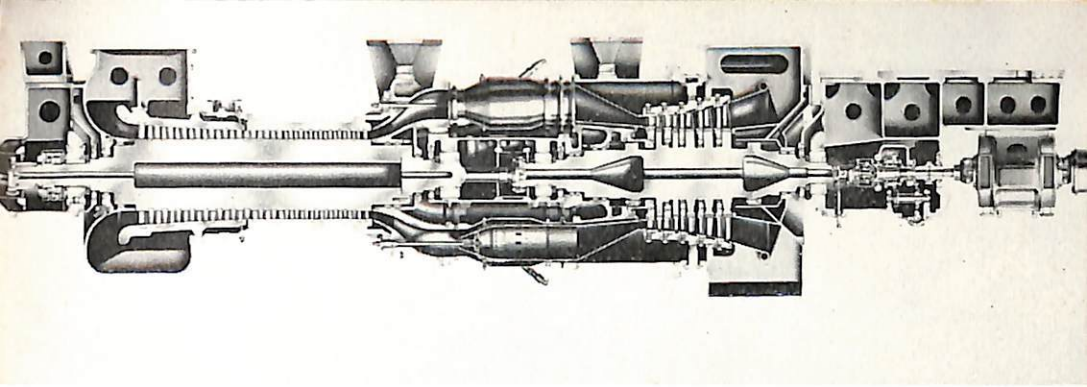
Bristol-Siddeley single-unit 3 mW. portable generator unit.

engines by the addition of a free turbine and reduction gearing. Among other detail problems which had to be dealt with was the risk of damage to the compressor or turbine by the entry of salt water spray to the air intake. This was overcome by careful design of the intake apertures and selection of materials for compressor blades, or protective coatings of ceramic material. It was also necessary to provide means of reversing the propeller drive for manœuvring purposes, which entailed designing gears and clutches capable of transmitting very high power. The Metro-Vick marine turbines were among the first to be put into regular production, and have been considerably improved in efficiency in recent years.

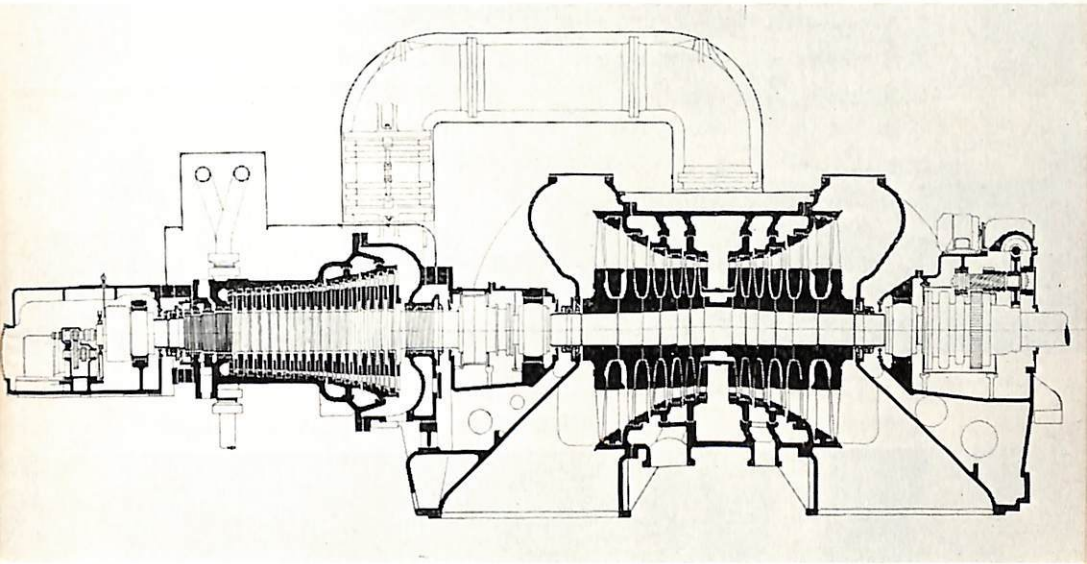
The adaptation of the Bristol-Siddeley Proteus engine to marine work was started in 1954, and it was later selected as the propulsion plant of the *Brave* class of fast patrol boats of the Royal Navy. In the preliminary bench testing of the engine, the most adverse conditions likely to be encountered at sea were simulated, including contamination with sea water. Apart from protective coating of the compressor and turbine blades, the intake ducts were fitted with "splitters" which combined effective water separation with silencing of the air flow. It was also found desirable to provide "inching" motors (generally known as "turning gear" in marine practice) to the engine so that when not running under power, it could be slowly rotated from time to time to prevent "brinelling," or local pitting, which can cause deterioration of ball or roller bearings.

The *Brave* patrol boats are each fitted with three Proteus turbines, driving individual propellers through V-drive reduction and reversing gearboxes. A primary reduction gear fitted to the engine gives a speed of 5,000 r.p.m. at the output shaft to the gearbox. The original Proteus marine turbine was originally rated at 3,000 shaft h.p., but has been progressively stepped up to 4,250 h.p. and the *Brave* boats, with their three engines, can attain speeds in excess of 50 knots.

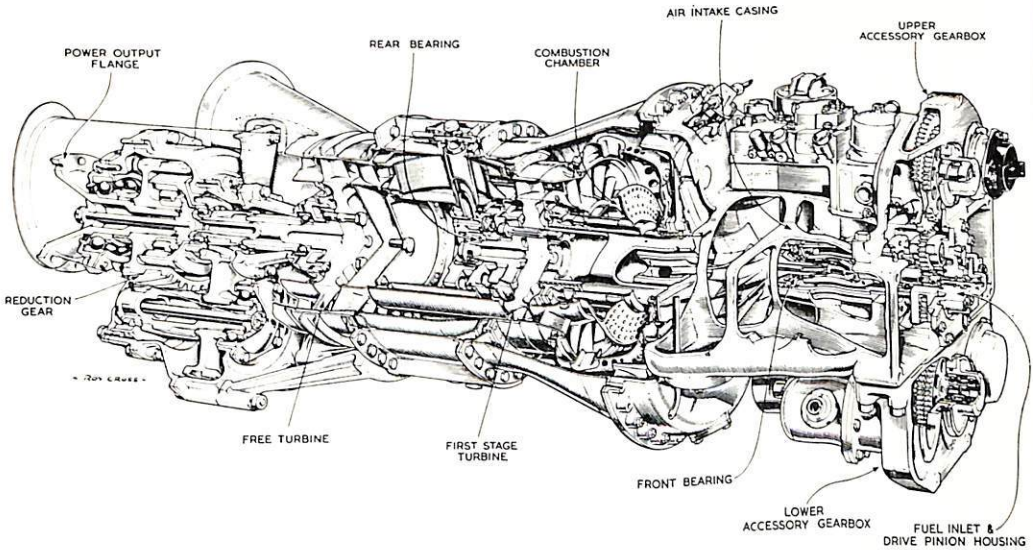
In the *Vosper* 88 ft. patrol boat, two Proteus engines are used in conjunction with two diesel engines driving into the same gearboxes, the latter being used for manœuvring and long-range cruising, while the turbines are available for full speed when required.



Sectional elevation of L51C industrial gas turbine (A.E.I.).



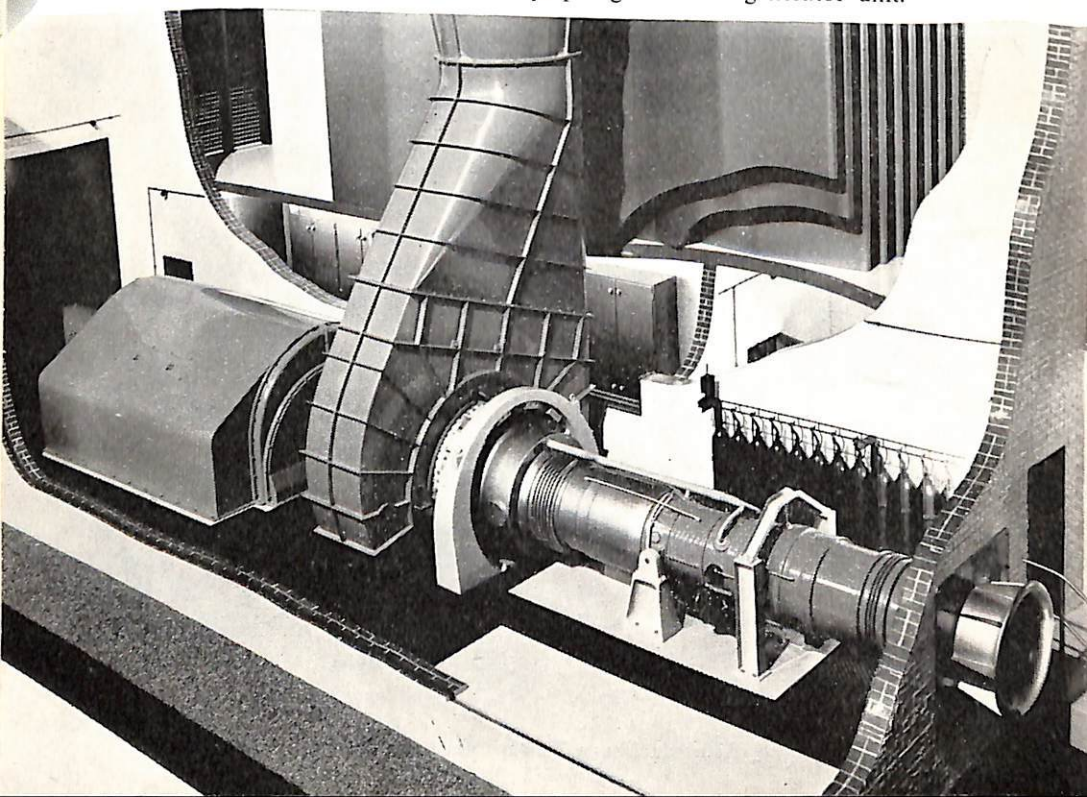
Cross-section of 60 mW two-cylinder balanced flow reheat turbine (A.E.I.)



The Blackburn Turmo 500 turbine.

(*Above*) An early experimental gas turbine-driven naval gunboat running at full speed.

(*Below*) The Bristol-Siddeley Olympus gas turbine generator unit.



The Olympus engine, also being developed for marine use, is expected to produce over 20,000 h.p. for a total weight of 6¼ tons and an overall length of 18 ft.

Gas turbines have also been successfully applied to the propulsion of merchant ships, where the important consideration is not obtaining the utmost power and speed, but economical and trouble-free running on long voyages. Some of the turbines used for this purpose do not operate on the internal combustion principle, strictly speaking, as the combustion of fuel does not take place in the turbine itself. This is carried out in a separate engine of the " free-piston " type, with no cranks or other rotating parts. Its function is to serve as an air compressor, and the air which it delivers, augmented, expanded and heated by the addition of its exhaust products, is fed to a turbine which differs only in detail from a steam turbine.

In principle, the use of a reciprocating compressor, or " gasifier " as it is called, in place of the rotary compressor and its turbine, might be regarded as a retrogression, but it enables fuel economy to be improved, and temperature difficulties to be reduced, in turbines which are not called upon to work at the highest possible power output. The space occupied by the turbine and gasifier is still much less than that required for a steam plant of comparable power, a very important consideration in cargo vessels and tankers.

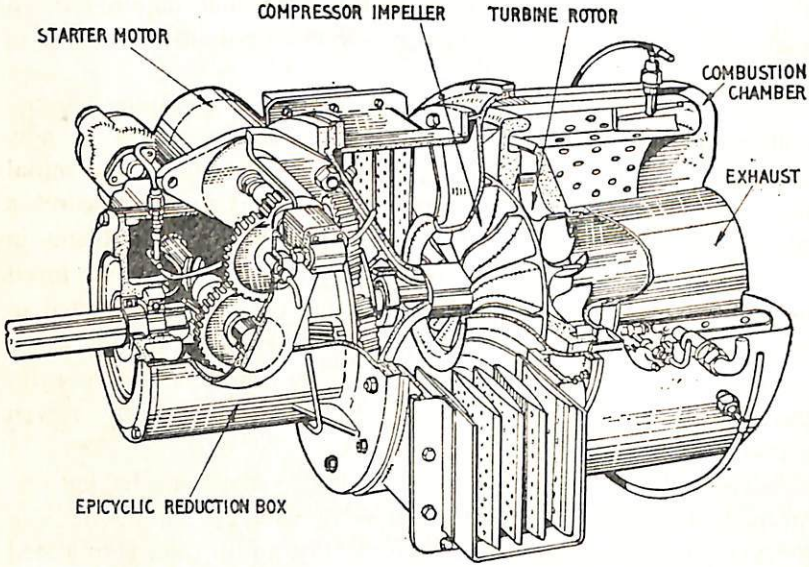
Another form of gas turbine which does not employ internal combustion is the exhaust-driven turboblower, which is now extensively applied for charging reciprocating engines. The initial development of this engine owes a great deal to the researches of Rateau, and it was many years before the detail problems in its design were successfully overcome, but it is now produced in several forms for air, land and marine use. It can be fitted to engines of standard design, to enable their power output to be increased up to as much as 20 per cent without imposing extra load, such as would be involved with mechanically driven superchargers.

The exhaust from the engine is led to a turbine having one or more stages, so designed as to work with the minimum back pressure. On the same shaft as the turbine, an impeller is mounted to serve as a centrifugal blower, which supplies air under pressure

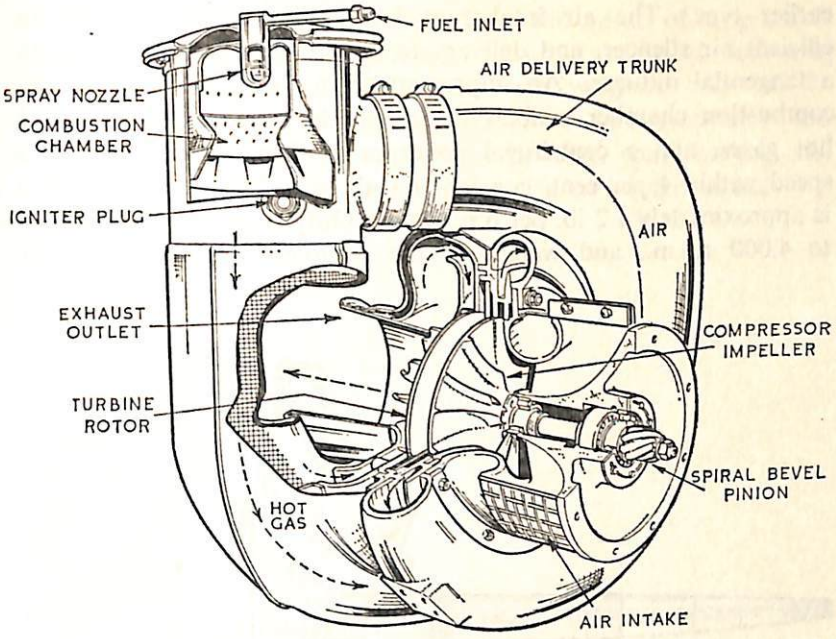
to the engine intake. As the limited factor in the power of an aspirated engine is its ability to draw in air by the pumping action of its own cylinders, or in other words "breathing," the increased power obtainable by supercharging is extremely valuable in enabling an aircraft to gain altitude, or ships and vehicles to attain higher speed.

While the progress of the gas turbine in the production of high power performance has been most impressive, its development in relatively small sizes has not been neglected. There are several types of turbines now available producing power outputs of less than 100 h.p., which for certain purposes have advantages over the existing piston engines of comparable power. Generally speaking, the fuel consumption of these small engines is rather high, as their thermal efficiency cannot be made comparable with that of the large turbines, but they have a very high power output in relation to their size and weight.

One of the first all-British engines in this class was the Budworth turbine, which was first produced in the early 1950's. It employed a single-stage turbine rotor of the radial inward-flow



The Mark II Budworth 70-90 h.p. turbine.

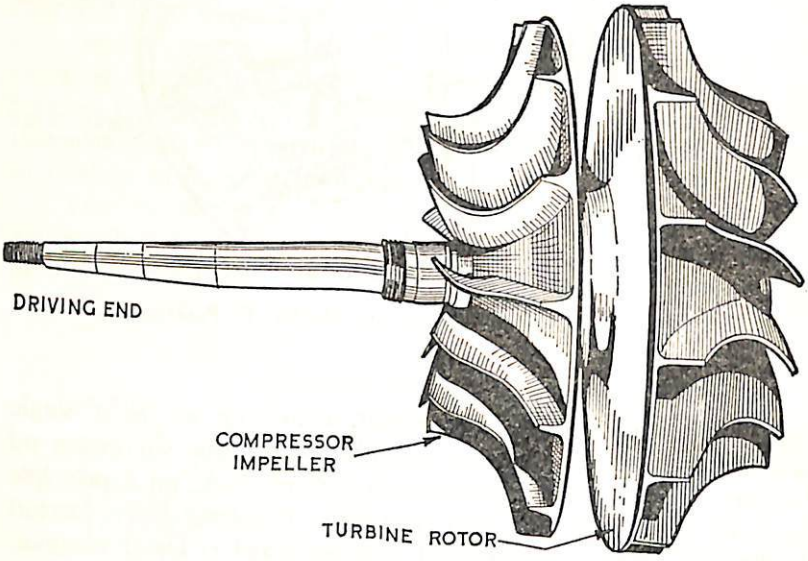


The Mars 50 h.p. turbine by Messrs. F. Perkins.

type, and a centrifugal compressor, delivering air to a single annular combustion chamber provided with three vaporising oil burners. These operate at relatively low pressure, on a principle basically similar to that of a blow-lamp or picnic stove, instead of the high pressure mechanical atomiser usual in larger turbines. A unique feature of this turbine was that it did not need electrical ignition, as it could be started with a match and an oil-soaked rag applied through an aperture in the combustion casing, while being run up to speed by a hand crank on the reduction gearbox. The turbine used diesel oil and developed 40 to 60 h.p. at a rotor speed of 45,000 r.p.m., reduced to 2,125 r.p.m. at the gearbox output shaft.

The present form of the Budworth turbine, the Mark II, develops from 70 to 90 h.p. and is improved in many details. It is equipped with electric spark ignition, and either hand or electric starting gear, also an epicyclic reduction gearbox which gives a co-axial drive instead of the right-angled drive of the

earlier type. The air intake, at both sides, is fitted with an efficient air silencer, and delivery from the compressor is through a tangential diffuser. An improvement in the flame tube of the combustion chamber enables the casing to be shielded from the hot gases, and a centrifugal governor is fitted which maintains speed within 4 per cent. constant on all loads. Fuel consumption is approximately 1.2 lb. per h.p./hour. Output speed is from 3,000 to 4,000 r.p.m., and weight of the complete engine is 100 lb.



Single-unit turbine and compressor shaft unit of Mars turbine.

Another small turbine is that produced by Perkins Engines Ltd., under exclusive European licence from the Solar Aircraft Company of California, and known as the Mars gas turbine. It has a rated output of 50 h.p. and a rotor speed of 40,000 r.p.m., reduced by spiral bevel gearing to 4,400 r.p.m. at the output shaft. Like the previous type, it has a single-stage radial inward-flow turbine rotor and a centrifugal compressor. It runs on diesel fuel, paraffin, or low grade petrol. The dimensions are $24\frac{1}{2} \times 17 \times 22$ in. and the weight 98 lb.

This turbine can be supplied in the form of a portable pumping set for fire or salvage purposes, capable of delivering 500 gallons per minute at 100 p.s.i., and weighing only 180 lb. all-on; also as an electrical generator or air compressor set. The exhaust gases can be applied for de-icing, space heating and drying purposes, also for producing a fog or smoke screen.

Chapter VIII

PROSPECTS FOR FUTURE DEVELOPMENT

THE world's power production, in terms of either horse-power or wattage, has now reached astronomical figures, and its rate of increase is likely to reach a still higher tempo in the future. But we have as yet touched only the fringe of possible power development, either from natural sources, combustion of fuel, or nuclear power. In many parts of the world there is a crying need for improvement and better organisation of water supplies, for the preservation of human and animal life, irrigation of arid land to promote agriculture, and the control of disastrous floods. Nearly all water development schemes give an opportunity for production of hydro-electric power as either a main or by-product, and what are commonly known as the under-developed regions offer a promising field for increasing both the fruits of the earth and the power to develop industry. It is fairly certain, therefore, that the water turbine will continue to be one of the most important means of power production.

Many of the largest rivers in the world still flow practically unhindered to the sea, and their potential power is unharnessed. The rain and melting snow from many great mountains is largely allowed to run to waste. Yet both are capable of contributing to power which might make the Sahara and Gobi deserts into fertile fields, and the frigid wastes of Greenland and Siberia not only habitable, but also capable of cultivation. Australia, which presents perpetual problems with alternate drought and flood, and has a vast interior region which is almost entirely waterless, might possibly be greatly enriched if even a partial solution to these problems could be achieved.

Such schemes would involve colossal expense and probably a long time to develop; but "man's reach should always be beyond his grasp," and the vocabulary of the progressive engineer has never included the phrase "it can't be done." Though local sources of water supply may be subject to variation through climatic and geological changes, the continuous evaporation of water from the oceans, and its recondensation on the earth as rain or snow, will not fail so long as the sun continues to shine. Water power, therefore, is the nearest possible practical approach to "perpetual motion."

Steam and gas power, which rely on the consumption of coal, oil or natural gas, is also capable of being exploited much more fully than it is at present, but as supplies of these fuels are not inexhaustible, and cannot be replenished by any means known to man, a time must come when they will cease to be available. It is possible that new fuels might be produced from vegetable or other organic matter, but whether this could be done economically enough to make it worthwhile is open to question. Nuclear power will probably supersede engines burning ordinary fuels for most large-scale applications, particularly if it can be released from the shackles imposed upon it at present by national and international politics.

Direct application of the sun's energy to produce power has long been known to be possible, and a good deal of attention is now being paid to its development. In tropical regions, where the sun can be relied upon to shine bright and hot during most of the year, experimental solar power plants, in which converging mirrors are used to focus heat on a steam generator have given very promising results. It is also possible to make use of the photo-electric properties of certain elements, such as selenium, to energise solar cells, and these are already used to provide current for radio and other instruments in space satellites. But so far as is known, the utilisation of solar power in any form on a large scale has hardly yet been envisaged, due to the colossal size and cost of apparatus in relation to power produced.

Much the same applies to the application of wind power on a large scale, quite apart from the temperamental nature of the wind, in which the fury of a hurricane may alternate with

long periods of dead calm during which no windmill, large or small, would make a single turn. Even assuming that an average performance over a given period could be relied upon, the size of a windmill to produce a substantial power output is so large as to make it hardly practicable. Some large experimental windmills have been built in various parts of the world but, so far as is known, none have paid off their initial cost of construction, and one at least was destroyed in a tornado.

The possibilities of tidal power have often been the subject of serious discussion, and there are prospects that this might be developed profitably in the future. Though the tides vary in height through seasonal and other influences, they ebb and flow with a complete certainty and regularity, so that their ability to produce a definite minimum amount of power would be assured. In the old days, tide mills were often used for grinding corn or other small power duties Their most favourable locations would be in the tidal estuaries of large rivers, where the normal flow of water augments the head of water on the ebb tide.

Tides are generally high around the coasts of Britain, and particularly in the Severn estuary, where they occasionally reach a height of between 50 and 60 feet. It is obvious that in conjunction with the enormous volume of water flowing, this represents a very large amount of potential power if it could be harnessed effectively. Some years ago, there was a scheme put forward for the construction of a dam or weir across the estuary near its emergence into the Bristol Channel, to enable this to be done: but so far the "Severn Barrage," as it was called, has not materialised.

There are several practical difficulties in the effective utilisation of tidal power, the most obvious being that the head of water varies from full to zero, and only a fraction of the time cycle can be usefully employed. Most turbines work most efficiently on a constant head of water, and though their speed can be controlled by suitable design of variable-pitch blades or guide vanes, this puts a very heavy duty on governors and control gear. In cases where power is obtained on both ebb and flow tides, reversible turbines, or complicated gates or sluice controls, are necessary.

But in any of these power schemes so far envisaged, it is fairly certain that turbines of some kind will be used to convert their potential energy into mechanical power. The only thing which could conceivably supersede the turbine would be complete elimination of the mechanical stage of conversion, such as *direct* application of heat, light, or nuclear power to produce electricity on a large scale without the medium of any form of engine. At present the prospect of so revolutionary a development is remote.

While the most important application of the turbine is obviously in large sizes and high powers, its usefulness in smaller sizes and more modest duties should not be overlooked. Apart from the comparatively low-powered turbines which have already been described, such as those used as auxiliaries to larger plants, or as portable power units, there are now many types of quite diminutive size used in industry. Where compressed air supply is available, it is often used to drive grinding and other appliances in which extremely high speeds are essential.

The finishing of hardened dies for casting, presswork or plastic moulding can be done with hand-operated tools driven by impulse turbines no more than 2 in. diameter and running at speeds up to 100,000 r.p.m. These are handier and lighter than equivalent electric-driven tools, few of which are capable of running at speeds best suited to tiny grinding wheels. Very fine drilling operations, such as for the injector nozzles of diesel engines, are sometimes carried out by turbine-driven machines, in which not only the high speed, but also the limited torque, is a great advantage. Whereas tiny drills, driven by ordinary methods, are very liable to break if they tend to jam in the hole, the turbine-driven drill is sensitive to the least change in resistance, and will stall rather than break.

This delicacy of touch is also very useful in machines for winding coils of ultra-fine wire, as used in miniature electronic apparatus. In this case the air pressure applied to the turbine is adjusted so that the torque obtained is just below the breaking-point of the wire. That instrument of torture, the dentist's drill, can now dispense with the cumbersome arrangement of belt or flexible-shaft drive, by using a tiny air or water turbine in the handpiece. The increased efficiency of this device helps the dentist to do a better job and shortens the ordeal for the patient.

In other low and medium-power fields, there are indications that the turbine will find many new applications. The development of the gas turbine motor car is proceeding steadily.

Metallurgical difficulties in the production of turbine blades, though not entirely eliminated, are yielding to patient research, and methods of producing rotors in one piece complete with blades, by machining or precision casting, are being developed.

Progress in engineering, generally speaking, is evolutionary rather than revolutionary. It takes a long time for any new principle, method or process to become firmly established and to supersede all others. The piston engines which, in spite of their limitations, have given long and faithful service, may not become extinct for many years yet, but it is fairly certain that the turbine, in all its many forms, is the engine of the future.

A notable event in the development of gas turbines for application to automobile propulsion was the successful performance of the Rover-B.R.M. car in the Le Mans 24-hour race in 1963. This event presents the most severe test of both speed and stamina of any in the motor racing calendar. The fact that a turbine-driven car, while still in the experimental stage, and new to track conditions, proved to be a formidable rival to piston-engined cars, demonstrates the reliability as well as the power performance of the turbine. After completing the race at an average speed of 107.84 m.p.h. for the full 24 hours, the turbine was in excellent condition, and would undoubtedly have been capable of running for a much longer period at the same speed.

The turbine employed in the car followed the same general principles as that of earlier Rover experimental turbines, but with several detail improvements. It comprised a compressor turbine unit, located at the forward end, together with auxiliaries such as fuel and oil pumps, driven from the compressor shaft, and the gearing for the electric starter motor. At the after end is the power turbine, which drives the transmission gearbox through helical reduction gearing. An expansion joint of the metal bellows type is fitted between the two turbines.

The arrangement of the turbine is shown in the diagram, which is simplified for explanatory purposes, with the omission of details such as the ball and roller bearing of the compressor and power turbine shafts. Air enters through apertures at the

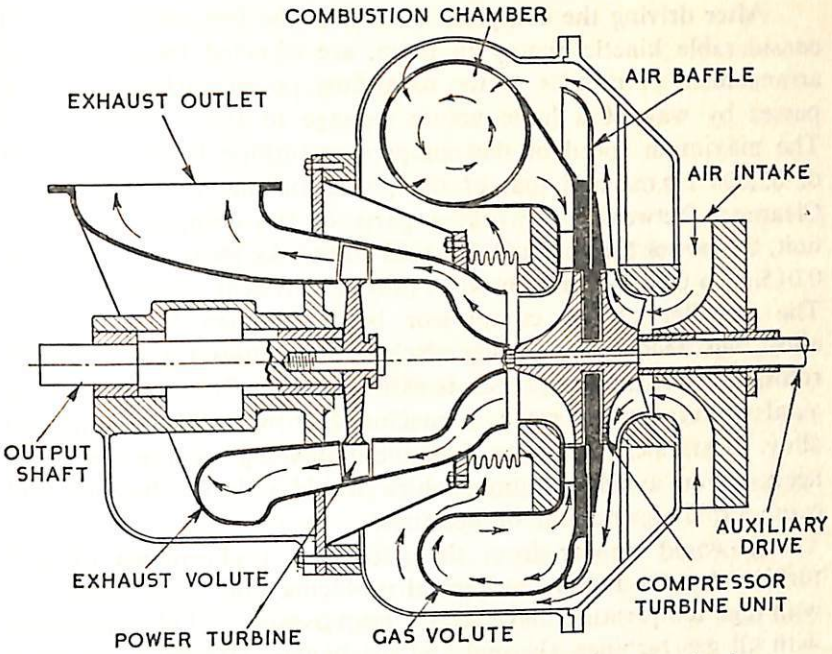


Diagram showing the arrangement of the gas turbine in the Rover-B.R.M. racing car.

sides of the compressor casing, and through an annular passage is directed into the single-stage centrifugal compressor. This is mounted back-to-back with the turbine rotor, with a separating partition between them, on the shaft which carries the auxiliary drive pinion. After compression, the air passes radially over a dish-shaped baffle into a volute leading to the single combustion chamber. This is located crosswise over the upper part of the casing, and contains a cylindrical flame tube, having the atomiser and igniter fitted at one end, and apertures in its side to admit primary air for combustion, and also extra air for dilution and cooling. Fuel is sprayed into the primary zone, where it mixes with sufficient air to ensure complete combustion after initial ignition. The flame temperature is too high to be manageable at this stage, but by mixing with the remainder of the air in the dilution zone, its temperature is reduced and its volume augmented so that it can be ducted through guide vanes to the inward-flow radial turbine.

After driving the compressor turbine, the hot gases, still with considerable kinetic energy in them, are directed by an annular arrangement of nozzles to the axial-flow power turbine. It then passes by way of a large volute passage to the exhaust outlet. The maximum speed of the compressor turbine is in the region of 65,000 r.p.m., and that of the power turbine is 40,000 r.p.m. Clearance between the working parts of the compressor-turbine unit, the power turbine, and adjacent stationary parts, varying from 0.015in. to 0.075in., is allowed to prevent physical rubbing contact. The impeller of the compressor is of high-tensile aluminium alloy, but heat-resisting alloy steels are essential for the turbine rotors ; that of the compressor is cast in Ni-base 713c alloy, and the axial power turbine rotor is machined from solid Nimonic 90 alloy. Extremely accurate dynamic balancing of the rotors is necessary to avoid vibration, which would reduce efficiency and cause rapid destruction of bearings.

It would appear from the successful performance of this turbine that the major mechanical problems, and those associated with high temperature, have largely been overcome, but in common with all gas turbines, thermal and mechanical efficiency still need to be much improved, to enable them to compete on an equal footing with piston engines. The fuel consumption of the Rover turbine in the Le Mans race was 7.0 miles per gallon, using kerosene fuel. About two-thirds of the total power developed from the combustion of the fuel is absorbed internally, most of it in driving the compressor. Further improvements indicated include the development of effective heat exchangers to make use of some of the heat wasted in exhaust, and detail modification of turbine blades and gas passages.

At present there is no provision for the classification of turbine cars in racing events, so that a fair comparison of their performance with piston engines cannot be assessed. The technique of driving cars with turbine engines is different to those of orthodox cars, as the engine, having an enormous amount of momentum in its moving parts, cannot be used as a brake. But the loads on the working parts are much lower, and there are no impact stresses or reversal of forces as in piston engines ; lubrication and cooling problems are in many respects simpler, so that both the reliability and durability of the turbine car may be major points in its favour.

GLOSSARY OF TECHNICAL TERMS

Absolute pressure : the pressure of a gas or liquid, measured from zero (total vacuum) ; in other words, approximately 14.7 lb. per square inch higher than the pressure shown on an ordinary pressure gauge.

Acceleration : rate of increase in velocity, due to gravity or other applied force. Expressed in ft. per sec. per sec.

Aerodynamics : the science of air or gases under conditions of motion, or bodies moving through air or gases.

Aerofoil : a blade, vane or fin designed to move through the air, or to translate force produced by the motion of air.

Afterburner : a device for increasing the thrust of a jet engine, by burning fuel in the exhaust stream to augment its volume.

Air cooling : extraction of unwanted heat by air flow.

Air pump : any pump for air or gases, but mainly applied to the pump used to extract air and condensate from the condenser of a steam engine.

Alloys, high temperature : special kinds of steel designed to resist oxidation and retain strength at extremely high temperatures, as in gas turbine blades (see Nimonic alloys).

Alternator : an electric generator producing alternating current (a.c.).

Altitude effect : loss of power in any form of engine relying on atmospheric air to support combustion, due to reduction of barometric pressure at high altitude.

Anemometer : a form of windmill used to indicate or register the speed of the wind.

Aspirated engine : any engine which " breathes " normally by self-generated suction, without added " boost " provided by a supercharger or other form of compressor.

Athodyd : abbreviated form of " aero-thermo-dynamic-duct." A form of internal combustion reaction engine without mechanical moving parts, relying on speed through the air to force air and fuel into its combustion chamber (see Ram-jet engine).

Atomiser : a device for spraying fuel in a finely divided state into a furnace or combustion chamber to ensure thorough mixing with air for complete combustion.

Augmented power : increase of shaft power by supercharging, or reaction thrust by afterburners.

Axial flow : in a compressor or turbine, flow of air, gas, or steam in a direction substantially parallel to the shaft.

Back pressure : residual pressure of steam or gas after all possible work has been extracted from it, or any unwanted pressure tending to oppose or restrict flow and thereby reduce efficiency.

Balancing : in the mechanical sense, the elimination of unbalanced forces, couples or moments in moving bodies. Pressure balancing consists of the cancelling of forces tending to cause thrust or movement due to fluid pressure.

Barometric pressure : normally, approximately 14.7 lb. above absolute zero, but varying according to altitude above sea level, and atmospheric conditions.

Blades, turbine : specially shaped aerofoils or hydrofoils attached to a rotor, to convert pressure, velocity or reaction into mechanical motion.

Bleed : the deliberate leak-off of high-pressure fluid from a steam or air system for control or other purposes.

Boost : artificial increase of intake pressure by supercharging, or " ramming " by rapid motion through the air.

Boundary layer : the layer of fluid which adheres to the walls of a passage or other body subject to fluid flow, tending to cause friction or restriction.

Boyles' law : one of the basic laws of gases, which specifies that " the volume of a given mass of gas at constant pressure is inversely proportional to the pressure to which it is subjected."

Centrifugal force : the force acting outwards from the centre in a rotating mass.

Charles' law : one of the basic laws of gases, which specifies that " if a gas is heated at constant volume, its pressure increases."

Combustion chamber : a closed or partially closed vessel to which air and fuel are admitted and ignited.

Compound engine : a steam or other fluid pressure engine in which expansion takes place in two or more stages (see Triple- and Quadruple-expansion).

Compression-ignition : ignition by heat produced by compression of air, without other aid, as in the diesel engine.

Compressor : a machine for pressing air or gas into reduced space and thereby increasing its pressure.

Condensate : water produced by condensation of steam.

Condenser : in steam engines, a device for cooling and liquefying exhaust steam (see Heat exchanger).

Constant pressure cycle : the working cycle of an engine in which expansion takes place without increase of pressure.

Constant volume cycle : the reverse of the above, in which pressure increases without change of volume.

Continuous combustion : usually employed in constant pressure engines: the reverse of intermittent combustion.

Corrosion : wastage of metal due to oxidation or other chemical action.

Cruising turbine : in marine practice, a small turbine, geared or otherwise detachably connected to the propeller shaft, used for reasons of economy when full engine power is not required.

Cycle : the rotational or other functional period in which all phases of operation are carried out in regular sequence.

De-aeration : the extraction of air from steam or feed water.

Diesel : an engine purporting to work on the principles specified by Dr. Rudolph Diesel ; applied loosely to all compression-ignition engines.

Distillate : fuel or other liquid produced by distillation.

Dummy piston (or rotor) : a pressure-balancing device, such as a turbine rotor without blades, on which pressure acts to produce end thrust opposing that of the actual turbine.

Dynamo : any form of electro-mechanical generator, but usually one which produces unidirectional current (d.c.).

Economiser : in steam plants, a form of feed water heater, usually

located in the smokebox or uptake, to utilise heat which would otherwise be wasted.

Efficiency : a measure of performance, i.e., *mechanical,* percentage of power left after deduction of frictional losses ; *thermal,* percentage of power in relation to energy theoretically obtainable from combustion of fuel, and *volumetric,* power in relation to size or capacity of engine. These terms are also applicable in reverse to compressors or similar machines.

Electric ignition : a means of initiating combustion in a gas turbine or piston engine, usually by means of a high-tension spark across an air gap in a sparking plug, or an incandescent resistance heater.

Erosion : as distinct from corrosion, wastage of metal or other material caused by abrasion or other mechanical action.

Exhaust : the efflux of gas or steam after all possible work has been extracted from it in an engine.

Flame tube : a combustion chamber in tubular or elongated form.

Flexible coupling : a device for connecting driving and driven shafts, while allowing for some degree of misalignment, or relative movement (see Universal joint).

Flume : a conduit, chute, or channel for water (see Penstock).

Fir tree blade root : a specially shaped root on a turbine blade, comparable to an inverted fir tree, to lock it in a similar shaped slot in the rotor, against the stress set up by centrifugal force.

Foot-pound : the unit of mechanical force : work done in lifting 1 lb. through a height of 1 foot.

Free piston engine : a reciprocating internal combustion engine, having no mechanical rotating parts, used mainly as a compressor or gas generator.

Free turbine : in gas turbines, a secondary turbine capable of independent rotation in relation to the primary turbine which drives the compressor.

Fuel-air ratio : the proportions of air and fuel necessary to produce a combustible mixture.

Gas generator : in gas turbines, a means of producing a large volume of air-fuel mixture, or pre-burnt products of combustion, for driving a turbine.

Gearing: strictly speaking, a train of toothed wheels used to vary speed and torque, but also applied to any form of mechanical transmission system.

Gland: a device to prevent escape of pressure around a sliding or rotating shaft.

Governor: a regulating device to control engine speed, generally by the application of centrifugal force.

Guide vanes: fixed or movable blades to direct the flow of water or gas in a turbine or compressor.

Gravity, or gravitational force: attraction to the earth. (Acceleration due to gravity = 32 ft. per sec. per sec.)

Heat exchanger: a means of heating or cooling air, gas or steam by conduction from another fluid at a different temperature, usually by way of a bank of tubes or other large area of surface (see Condenser and Radiator).

Heat transfer: conduction of heat to surrounding metal, or other adjacent substance, as in a heat exchanger.

Helical gear: a form of cylindrical toothed gear having the teeth cut at a spiral angle.

Helicopter: an aircraft lifted by means of a powered vertical airscrew.

Herringbone gear: a gear of the double-helical type, i.e. with teeth of opposed spiral angle meeting in the centre.

Horse-power: the standard measure of power, or the rate of work, equal to 33,000 ft. lb. per minute.

Hovercraft: an amphibious vehicle in which a cushion of air is used to produce levitation, or limited lift.

Hydrofoil: the counterpart of an aerofoil, but designed to work in water instead of air.

Ignition: the initial stage of combustion, by application of a flame, spark or glow heater to a combustible fuel or air-fuel mixture (see Electric ignition).

Impeller: a rotor with radial or tangential blades, as used in a centrifugal pump or compressor.

Impulse: a force causing, or tending to cause, movement; usually of a transient or intermittent nature.

Inertia: the reluctance of a body to change its state of rest, or rate of motion.

Incidence: the angle at which an aerofoil or hydrofoil is presented to the flow of fluid, or to its line of motion when moving through a fluid.

Intercooling: extraction of unwanted heat from air or gas between stages in a compound-stage compressor.

Intermittent (combustion, impulse, motion): non-continuous, operating in repeated bursts or cycles.

Irrigation: controlled supply and distribution of water to otherwise arid expanses of soil, to promote agriculture.

Jet: literally, any form of nozzle, spout or orifice through which fluid is expelled, or the stream of fluid thus expelled (Latin, *jacio*, to throw).

Jet engine: any form of engine (not necessarily a turbine) which produces a jet having sufficient force and volume for propulsion.

Jet propulsion: movement caused by the reaction of a jet.

Joules' mechanical equivalent of heat: the theoretical standard of relation of heat and work. In the F.P.S. system of units, 1,440 ft. lb. of work are necessary to raise the temperature of 1 cu. ft. of water 1 degree C. (equivalent to 772 ft. lb. for a rise of 1 degree F.).

Kaplan turbine: a water turbine having helical blades, comparable to those of a ship's propeller.

Kerosene: a distillate of crude petroleum having a moderately high flash point, known in Britain as paraffin or lamp oil; suitable as a fuel for gas turbines.

Kilowatt: the unit of electrical power, equal to 1,000 watts.

Kinetic energy: the energy contained in a solid, liquid or gaseous body in motion, equal to half its mass multiplied by the square of its velocity.

Labyrinth packing: a means of providing a pressure seal in a gland without physical contact of working parts, or the use of resilient material.

Laminar flow: the tendency of fluids to flow in a direction parallel to the surface of passage walls, guide vanes, aerofoils or other boundaries.

Lubrication: reduction of friction by oil or other media introduced between rubbing surfaces.

Mach number: in aircraft terminology, a decimal figure indicating air speed in relation to the speed of sound (Sonic speed = Mach 1).

Megawatt: high-power electrical unit, equal to 1,000,000 watts.

Methanol: a form of methyl alcohol suitable for use as a motor fuel.

Michell thrust bearing: a form of bearing designed to withstand heavy end thrust or weight by the use of oil films introduced between discs and segmental pads.

Mixed flow turbine: a water, steam or gas turbine in which the direction of flow is oblique to the axis, or multi-directional.

Momentum: the tendency of a moving body to continue in motion in the same direction at the same speed. Expressed in terms of mass x velocity.

Needle head: a device for controlling the jet of a Pelton or other form of water impulse turbine (see Variable nozzle).

Negative work: necessary but unproductive work done in overcoming friction, back pressure or other resistance, thus reducing mechanical efficiency.

Nimonic alloys: special alloys for turbine blades, having high tensile strength and heat resistance.

Non-reversibility: most forms of turbines will run in only one direction, but some forms of water turbines can be reversed to act as rotary pumps.

Nozzle: the orifice of a De Laval, Pelton, or other impulse turbine.

Nuclear power: heat energy liberated by atomic fission.

Oil cooler: a heat exchanger for reducing the temperature of lubricating oil which has been heated by friction in bearings, or contact with hot metal.

Output: the total electrical or mechanical power available from an engine or plant installation after all losses are accounted for.

Overall efficiency: the percentage of power realised after deduction of thermal, mechanical and other losses.

Overshot wheel: a water wheel in which water enters at or near the top of its diameter.

Penstock: a water channel, usually narrow and enclosed (see Flume).

Performance : another term for the efficiency of an engine or power plant.

Petrol : a distillate of crude petroleum having a low flash point, used almost exclusively as a fuel for carburetted and spark-ignited internal combustion engines.

Petroleum : strictly speaking, crude mineral oil as originally obtained from the well, but often applied to semi-refined fuel oils and other distillates.

Pilot valve : a control valve, often used to operate larger valves through a servo-motor.

Prop-jet engine : an engine which produces both jet reaction and mechanical rotative shaft power.

Propulsive efficiency : thrust efficiency produced either by reaction or mechanical power.

Pulse-jet : a form of jet engine (not a turbine) in which combustion is intermittent.

Pump (fuel) : a mechanical pump for supplying fuel to the carburettor or atomiser of an engine; (lubrication) for supplying oil under pressure to the bearings of an engine.

Pumped storage : in hydro-electric systems, a means of conserving energy, and keeping electrical plant working at high efficiency, by using generators as motors to pump water back to the high-level reservoir when load demand is low.

Quadruple-expansion : in steam engines, utilisation of pressure in four stages to promote thermal efficiency.

Radiator : a form of heat exchanger which employs air as the transfer medium.

Ram jet : a simple continuous-combustion jet engine without mechanical moving parts (see Athodyd).

Reaction : force acting in opposition to applied motive force (vide, Newton : " Action and reaction are always equal and opposite ").

Reduction gear : any form of gear employed to reduce speed of rotation, and increase available torque in proportion.

Refractory materials : Ceramics or metal alloys capable of withstanding very high temperatures.

Reheat : application of heat (by a suitable heat exchanger) to make up losses between stages of a multiple-stage piston engine or turbine.

Retractable blades: in water turbines, blades which can be withdrawn into the hub of the runner for purposes of regulation.

Reversing turbine: a separate turbine in a marine installation, necessary for running astern, or rapid braking in emergency.

Rotor: any major rotating part in a turbine, generator or other machine.

Runner: the rotating part of a water turbine in which the blades are mounted.

Saturated steam: steam at its normal temperature in relation to pressure, without rise of temperature due to superheating.

Servo-control: operation of heavy mechanical controls by some form of relay or **servo-motor.**

Shrouded blades: turbine blades enclosed in an outer ring or shroud, to increase strength or avoid end losses of working pressure.

Silencing: reduction of exhaust noise by baffling or gradual expansion.

Skin friction: resistance to motion caused by boundary layer of fluid.

Solar power: mechanical or electrical power obtained by radiant or heat energy from the sun's rays.

Specific gravity: weight of a substance in relation to that of an equal volume of water.

Specific heat: the amount of heat necessary to raise the temperature of a substance one degree per unit of its mass.

Spider: a spoked frame to support a rotor or other machine component.

Spill nozzle: a form of control for a Pelton wheel by spilling or diverting the flow of water from the nozzle.

Starter, engine: an electrical, mechanical or pneumatic device for turning an engine at a speed high enough to start working under its own power.

Stop valve: a shut-off or regulating valve for steam, water, air or gas pressure.

Stress: force or impact tending to cause movement, deformation or breakage of a component.

Stuffing-box: a pressure-retaining gland in which soft packing or other resilient material is used.

Supercharger: a blower or compressor for charging the combustion chamber of an engine at a pressure above that of the atmosphere, or obtainable by aspiration alone.

Superheater: in steam plants, a heat exchanger in the boiler furnace for supplying additional heat to the steam, so that it is delivered at a temperature above that of saturation.

Supersonic speed: speed higher than that of sound.

Synchronising: matching the velocity of moving bodies, so that they are equal in speed to one another.

Thermodynamics: the science of heat as a means of producing mechanical energy.

Throttle: a restricting valve for controlling engine speed; not necessarily for shutting off pressure and stopping it completely.

Thrust: strictly, any motive force in a given direction; applied mostly to end or side loading of engine bearings.

Titanium: a light but strong metal, usually alloyed with other metals for use in turbine compressor blades and other parts.

Torque: force tending to produce torsion (twisting) or rotational movement.

Triple-expansion: in steam engines, utilisation of working pressure in three stages of expansion.

Tubular boiler: a type of boiler employing multiple tubes to provide a large area of heating surface.

Turbo-blower: a low-pressure compressor driven by a turbine.

Turbo-charger: a turbo-blower employed for supercharging a piston engine, generally working on exhaust gas.

Turbo-electric propulsion: in marine practice, electrical transmission of power to the propeller from one or more turbines.

Two-stage compressor: in gas turbines, a charging compressor with two impellers in series; or any compressor having two stages of compression.

Umbrella rotor: a rotor suspended from a spoked frame or spider like the ribs of an umbrella.

Undershot wheel: a water-wheel driven from the underside.

Universal joint: an articulated joint in a transmission system, allowing of angular movement between rotating shafts. Its basic form is known as a "Hooke's joint". (See Flexible coupling.)

Vacuum: literally, complete absence of air pressure, but any reduced pressure below atmospheric is termed "partial vacuum," and measured in terms of the height of a column of mercury which it will support.

Vaporising burner: as distinct from an atomising burner, one in which liquid fuel passes through heating tubes and becomes gasified.

Variable nozzle: a form of nozzle which can be adjusted in area by means of an internal tapered needle or other device.

Velocity: the rate at which a body changes its position in space; speed of motion in any direction.

Volute: a spiral or snail-shaped passage to promote a smooth change of directional flow in a rotary pump or turbine.

Vortex: the form assumed by a liquid when set in circular motion, as in a whirlpool, or the volute of a turbine.

Water jacket: a space around a combustion chamber or cylinder for the circulation of cooling water.

Water seal: a form of vacuum or pressure gland in which water or other liquid is introduced between working surfaces (see Labyrinth packing).

Windmill: a machine to produce rotary motion from the wind; a form of low-pressure air turbine.

Wind tunnel: an aerodynamic testing device, in which aerofoils or other objects are placed in an air stream to test resistance, lift and other characteristics.

INDEX

Absolute pressure (Appendix) 93
Aeolipile, 7, 8, 26
Aerodynamics (Appendix) 93
Aerofoil, 75
Afterburner (Appendix) 93
Air cooling (Appendix) 93
Air pump, 64
Alloys, high temperature (Appendix) 94
Altitude, 45
Anemometer, 4
Anglo-Iranian Oil Exploration and Producing Co., 76
Armstrong-Siddeley, 73
Artouste, 74, 75
Asea Electric Co., 58
Aspirated engine, 45
Associated English Industries, 67, 75
Athodyd (Appendix) 94
Atomiser, 49
Augmented power, 44
Automatic power stations, 77
Auxiliary machinery, 84
Axial flow compressor, 46
Axial flow turbine, 21

Back pressure, 72
Balancing, static and dynamic, 29
Balancing, pressure, 36
Barber, John, 41
Barometric pressure, 45
Bearings, 15, 54, 58
Beck, Sir Adam, power station, 62
Berkeley power station (Plate facing p. 64)
Berry, S. A., 20
Blackburn engines, 74
Blades, turbine, 29, 33
Blades, clearance, 27
Blades, materials, 92
Bleed (Appendix) 94
Boiler, 65
Boost (see Supercharging)
Boundary layer (Appendix) 94
Boving & Co. Ltd., 55
Boyle's Law (Appendix) 94
Branca, Giovanni, 9
Brave patrol boats, 80
Breast wheel, 13
Bristol-Siddeley Ltd., 73, 76
British Railways, 50
British Thomson-Houston Ltd., 38
Brown-Boveri Co. Ltd., 50
Brush Electrical Co. Ltd., 38
Budworth, D., & Co. Ltd., 82, 83
Burners, liquid fuel, 83

Centrifugal compressor, 46
Centrifugal governor, 23
Ceramic blade coating, 80
Charles' Law (Appendix) 95
Charmian, launch, 36
Circulation in boilers, 66
Clarke Chapman & Co. Ltd., 30
Closed circuit, 36, 65
Clunie power station, 55
Combustion chamber, 46
Compound engine, 31
Compressor, 43, 46
Condenser, 64, 65
Constant-pressure cycle, 42, 45
Constant-volume cycle, 42, 43
Controls, 23, 67
Cooling, 42
Corrosion, 45
Cruising turbine, 38
Cumulus turbine, 75
Curtis turbine, 38
Cycles, 42

Davey-Paxman & Co. Ltd., 65
De-aeration, 65
De Kempelen, Wolfgang, 26
De Laval, Carl Gustav Patrik, 11, 27, 29
Deriaz, Paul, 62
Diesel, Rudolph (Appendix) 95

Displacement engines, 2
Distillates, 75
Doble, W. A., 20
Double-bracket rotor bearings, 54
Draught, forced or induced, 66
Dreadnought, battleships, 35
Ducts, air, 80
Dummy piston, 31, 36
Dynamic balancing, 29
Dynamo (see Generator)

Economiser, 65
Edison, Thomas Alva, ix
Efficiency, mechanical (Appendix) 96
Efficiency, thermal (Appendix) 96
Efficiency, volumetric (Appendix) 96
Efflux (see Exhaust)
Electric ignition, 50
English Electric Co. Ltd., 37, 38, 53, 55, 56, 57, 61, 62
Ericsson, 27
Exhaust, 29, 68, 72, 76
Exhaust turbo-charger, 44
Escher-Weiss et Cie., 20

Failure, engine, 74
"Fir tree" blade root (Appendix) 96
Flame tube, 46
Flexible coupling (Appendix) 96
Fluid friction, 18, 29
Francis turbine, 23, 55, 58, 59, 60
Frazer-Chalmers & Co. Ltd., 38
Free-piston engine, 81
Free turbine, 75
Fuel atomiser, 46, 49, 91
Fuel consumption, 73, 92

Gach Saran oilfield power station, 76
Gas turbine, types, 40-50
Gearing, reduction, 26, 29
Generator, electrical, 51
Generator, gas, 81
Gilke turbine, 23
Girard turbine, 23
Gland, labyrinth, 36
Gland, packing, 36
Governor, centrifugal, 59
Governor, hydraulic, 61
Greenwood & Batley Ltd., 71
Guide vanes, 24

Heat exchanger, 64
Heat transfer, 69
Helical gearing, 36
Helicopters, 74
Hero of Alexandria, 6, 8, 26
"Herringbone" gears, 36
High pressure, 19, 64, 68
High temperature alloys, 45
Holzwarth, Hans, 43, 44
Horizontal shaft turbines, 54
Horse power, 73
Hydrofoil, 34
Hydro-mechanical governor, 61

Ignition (Appendix) 97
Impeller (Appendix) 97
Impulse turbine, 38, 70
Incidence, angle of (Appendix) 98
Intercooling (Appendix) 98
Intermittent combustion, 42, 43
Irrigation, 86

Jet (Appendix) 98
Jet aircraft speeds, 47
Jet aircraft propulsive thrust, 73
Jet engine, 46, 47
Jet engine, efficiency of, 73
Jet engine fuel consumption, 73
Jet nozzle, 18
Jet velocity, 27
Joule's mechanical equivalent of heat (Appendix) 98

Kaplan turbine, 23, 54, 58, 61
Kariba power station, 58
Kerosene (Appendix) 98
Kilowatt, 63
Kinetic energy, 2, 6, 10, 13, 18, 25, 27

Labyrinth gland, 36
Laxey water wheel, 15, 16, 17
Liquid flow, 18
Ljungstrom turbine, 37, 38
Low pressure compressor, 46
Low pressure turbine, 72
Lubrication, 38, 54

Mach numbers (Appendix) 99
Maintenance, 54
Mars turbine, 84
Mauretania, R.M.S., 70
Mechanical efficiency (Appendix) 96

Megawatt, 63, 68
Metals for turbine blades, 45
Methanol (Appendix) 99
Metropolitan-Vickers Ltd., 38
Michell thrust bearing, 58
Mixed flow turbine, 23, 56
Moss, Dr. S. A., 41, 43, 45
Murdoch, Richard, 10

Nasmyth, 26
Needle head jet control, 61
Negative work, 43, 45
Niagara power station, 52, 57
Nimbus turbine, 75
Nimonic alloys, 92
Non-reversibility, 39
Nozzle, control, 30
Nozzle, De Laval, 27, 28
Nozzle, diffuser, 61
Nozzle, Pelton, 20
Nuclear power, 69

Oil pump (Appendix) 100
Olympus turbine, 76
Output (Appendix) 99
Overall efficiency (Appendix) 99
Overshot wheel, 13
Owen Falls power station, 58

Palas turbine, 74
Palouste turbine, 74
Parsons, Sir Charles, 11, 30-38, 41, 46
Pelton wheel, 17, 19, 20, 21, 24, 27, 61
Perkins, F., & Co. Ltd., 84
Pilot valve, 59
Piston, 2
Pitch-backshot wheel, 15
Pneumatic turbine, 89
Pneumatic starter, 75
Power station, gas turbine, 76, 77
Power station, steam, 67
Priest Rapids power station, 55
Prop-jet engine, 47, 48
Proteus turbine, 76
Pump, fuel, 45
Pump, lubrication, 71
Pumped storage system, 61

Quadruple-expansion engine, 63

Ram-jet engine, 45
Rateau, 38, 44
Rateau exhaust turbine, 44
Rateau steam turbine, 38
Reaction turbine, 12, 27
Reduction gearing, 36
Refractory materials, 66
Reheat, 68
Reidler-Stumpf turbine, 38
Relay, hydraulic, 59
Retractable blades, 61
Reversing gear, 80
Rolls-Royce Ltd., 73
Rotor, 21
Rover turbines, 50, 90
Runner, turbine, 24

Savery, 8
Seewer regulating system, 61
Servo control, servo motor, 59
Shrouded blades, 29
Simple turbine, 7
Skin friction (see Fluid friction)
Skegsforsen turbo-generator, 58-60
Snowy T.I. power station, 56
Solar Aircraft Co. Ltd., 84
Solar power, 87
Specific gravity (Appendix) 101
Specific heat (Appendix) 101
Speed range, 68
Speed, rotational, 10, 11
Speed, linear or peripheral, 10, 11
Spider, rotor, 54
Spill nozzle, 24
Starting jet engines, 75
Steels, turbine construction, 45
Stolze turbine, 41
Stop valve, 30
Stresses, centrifugal, 42
Stuffing-box, 36
Supercharging, 44
Superheater, 65, 66
Synchronising, 59

Tachometer, 4
Temperature, gas, 42, 47
Temperature, exhaust, 48
Temperature, jet engine, 47
Temperature range, 47, 64, 68
Temperature, steam, 64
Temperature, turbine, 47
Thermal efficiency, 44
Thermodynamics, 44, 45
Thomson, 23
Throttle, 24
Thrust bearings, 36, 54, 58
Torque, 5

Trevithick, Richard, 10, 27
Triple-expansion engine, 63
Tubular boiler, 66
Tully Falls power station, 53
Tummel-Garry hydro-electric scheme, 55
Tunnel turbine, 54
Turbine, air, 89
Turbine, gas, 41
Turbine, impulse, 11, 37
Turbine, reaction, 11
Turbine, steam, 6, 7, 9, 10, 25
Turbine, water, 6, 34, 52
Turbine-driven aircraft auxiliary machinery, 73
Turbine-driven locomotives, 50
Turbine-driven hand tools, 89
Turbine-driven machine tools, 89
Turbine-driven ships, 69-70.
Turbinia, steamboat, 38, 39, 70
Turbo-blower, turbo-charger, 44, 81
Turbo-jet, 46, 73-74
Turbo-prop, 47, 73
Turbo-electric ship propulsion, 70
Turmo turbine, 75
Two-stage compressor, 46

"Umbrella" rotor construction, 54
Undershot wheel, 13

Vacuum, 33
Vaporising burner, 83
Variable nozzle, 61
Velocity, 2, 18
Vertical-shaft turbine, 54
Volumetric efficiency (Appendix) 96
Volute, 54
Vosper, patrol boat, 80

Water, physical characteristics, 17-18
Watt, James, 10, 23, 26, 41
Weight of engines, 71, 79
Westinghouse high-speed engine, 25
Whittle, Sir Frank, 44, 46
Willans high-speed engine, 25
Windmill, 2-6
Wind tunnel (Appendix) 103